Measuring Disaster Resilience: The Impact of Hurricane Sandy on Critical Infrastructure Systems

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ABSTRACT

Modern critical infrastructure (CI) systems are tightly coupled, resulting in unprecedented complexity and difficulty to predict, limit and control the consequences of disruptions caused by hazards. Therefore, a paradigm shift in disaster risk management is needed: instead of focusing on predicting events, resilience needs to be improved as a basis for adequate response to any event.

This paper starts from a definition of CI resilience that provides a basis for quantitative and qualitative decision support. For the quantitative modelling approach, which aims at measuring the resilience of individual CIs, we focus on two CIs of fundamental importance for disaster response: transportation and power supply. The qualitative framework details relations between CIs.

The results of this research are illustrated by a case study that analyses the impact of Hurricane Sandy. The findings highlight the need for a framework that combines qualitative and quantitative information from heterogeneous sources to improve disaster resilience.

Keywords

Hazard, Critical Infrastructure System, Resilience, Vulnerability Assessment, Decision Support, Hurricane Sandy

INTRODUCTION

Critical infrastructures (CIs) are lifeline systems, which greatly influence public welfare and economic prosperity (O'Rourke, 2007). CIs include the physical components (road networks; hospital buildings) and services that are provided via these components (transportation of passengers or good; health care). While (technical or physical) infrastructures can be defined as complicated networks (Hanseth, 2010), there is no unanimous definition integrating the service dimension, and including the question how infrastructure criticality is defined (Haemmerli and Renda, 2010). Despite the diversity of definitions, they all have in common that CIs are defined by their role for society (Rinaldi et al., 2001; Min et al., 2007): they support the services that are vital for life and sustainable economic growth.

Modelling and predicting CI behaviour is challenging for various reasons: each CI in itself is complicated; CIs are evolving as a part of technological changes and innovation; CIs are more tightly coupled than ever before (Rinaldi, 2004); governmental regulations and laws are changing; and models rely on data provided by governmental bodies and agencies and private industries, that only have limited interest in unveiling key weaknesses (Min et al., 2007). While this is already prominent in planning and forecasting, the even more challenging context of a crisis or disaster, including challenges ranging from lack of data to ad-hoc changes in behavioural patterns (Turoff et al., 2004), make it impossible to predict the consequences of a hazard event on CIs; or to limit its impact to a specific region or economic sector.

This paper focuses on the impact of Hurricane Sandy. The UN coordinate response to humanitarian disasters by using clusters that represent key functions (Stumpenhorst, Stumpenhorst & Razum, 2011). Logistics, Emergency Telecommunication or Water and Sanitation are linked to widely recognized CIs. Other functions, such as Protection or Recovery are more generic, showing that the needs the notion of 'criticality' changes, i.e., what is perceived what a community or society perceives as vital is prone to shifts. The most recent case is Typhoon Haiyan that hit the Philippines in November 2013. Response and disaster relief efforts were delayed by disruptions of communication lines, transportation systems or power blackouts (UN-OCHA, 2013). To respond to these challenges, and to be able to manage highly interlaced technical and socio-economic systems while responding to a crisis or disaster, communities, public authorities and infrastructure providers have to implement adequate risk management and mitigation strategies.

Critical infrastructure Resilience in Disaster Risk Management

As we cannot prevent hazards from happening, there is a shift in risk management: instead of reducing exposure or likelihood of a hazard event, decision-makers today more and more focus on improving resilience and/or reducing vulnerability (Birkmann, 2006; Kent, 2011). Although it is frequently used in different contexts, there is no generally accepted definition of resilience. Rather, the different concepts and methods to define and measure resilience reflect the diversity of fields, in which the term is used (Mitchell & Harris, 2012). In general, vulnerability can be understood as the characteristics of a system or asset that make it susceptible to the damaging effects of a hazard, whereas resilience refers to the coping capacity, including a dimension of learning (Johansson & Hassel, 2010; UN/ISDR, 2004). One of the most prominent aims of vulnerability assessments is improving preventative measures and allocating risk management resources in an efficient way, whereas resilience refers to the capacity to respond to change.

While for some authors, resilience is a factor that includes vulnerability (Klein, Nicholls, & Thomalla, 2003), we understand resilience as the ability of an actor, organization or system to cope with or adapt to stress (Pelling & High, 2005). In one of the earliest papers, Holling (1973) defined resilience as the ability of a system to absorb change while maintaining the same relations and characteristics. Today, this idea of maintaining or preserving structures has led to interpretations of resilience to reduce risk in the broad context of sustainable development (UN/ISDR, 2008). Instead of focussing on longer-term preparedness and development, this paper focuses on *disaster* resilience. We aim at understanding resilience of critical infrastructures in the context of a crisis or emergency, including changes in the needs of population and responders.

To provide decision support and manage risks, there is a need for a comparable concept of resilience that enables the identification of hotspots and provides clear indications for the allocation of scarce resources at a regional level as well as for different CI providers. Current approaches to assess CI resilience can be divided in two categories, predictive and empirical approaches. Predictive approaches model infrastructure systems including their interdependencies (Wang, Hong, & Chen, 2012). Computational models of CI networks are created and disruptions are simulated to assess the consequences. Due to the complexity of real infrastructure systems, these approaches often work with isolated parts of infrastructure systems or with theoretically constructed reference infrastructures.

To avoid these shortcomings, we will start from an empirical analysis assessing the resilience of CIs by analysing the consequences of hurricane Sandy within and across CIs. In a first step, we focus on a quantitative assessment of disruptions in individual level analysing infrastructure recovery and resilience. Secondly, we provide a qualitative assessment to get a better understanding about the interdependencies between the different CIs. Combining both parts, insights can be gained into the interplay between resilience and recovery

Understanding Resilience in Context: The Case of Hurricane Sandy

Hurricane Sandy made landfall on the U.S. East Coast in the evening of the 29th of October 2012 (W. N. Bryan, 2012). On the 30th of October 2012, about 8.7 million customers were affected by power outages (Mühr et al., 2012). Information and communication infrastructure, especially wireless and Internet infrastructure, also suffered serious damages (Heidemann, Quan, & Pradkin, 2012). Power outages affected other infrastructures, for example oil and natural gas production or transportation: refineries were shut down and oil terminals, gas tanks and pipelines were inoperable due to power loss (Bryan, 2012c). Overall, the economic impact of Hurricane Sandy is estimated to add up to 50 billion US$ (Zandi, 2012).

To assess CI disaster resilience, information about the context and its expected evolution needs to be combined with information about the hazard. Therefore, our analyses are based on data from official situation reports, published, e.g. by the U.S. Department of Energy, the Federal Emergency Management Agency (FEMA), and the Federal Communications Commission (FCC). Additionally, reports from research institutions and data provided by company websites, such as the Metropolitan Transportation Authority (MT) New York, NJ Transit, Con Edison etc. was used and completed by data from media coverage.

A FRAMEWORK FOR RESILIENCE ASSESSMENT IN DISASTER RISK MANAGEMENT

In this section, we outline the framework for resilience assessment as a part of the disaster risk management. In engineering and modelling approaches, resilience is typically measured via indicator frameworks, which describe qualitative and quantitative properties of the system under scrutiny (Bruneau et al., 2003; Reed, Kapur, & Christie, 2009). Those properties are usually assumed to be stable, and most frameworks use static indicators derived from statistical data on a national or broader regional scale. Generalising this approach in the context of disasters assumes that resilience is stable, and not prone to sudden changes and shifts (Adger, 2006).

Communities or societies are, however, complex systems and characterised by dynamic behaviour, non-linearity and emergence (Einarsson & Rausand, 1998). Along with the increasing pace of societal change, dynamic resilience assessments have become increasingly important (Leichenko & O'Brien, 2002). Moreover hazardous events themselves can be understood as shocks that drastically change a system's behaviour: natural disasters are typically characterised by their sudden onset and unexpectedness. Therefore, we propose an approach that acknowledges that the dynamic nature of resilience, which will change with the phases of disaster management.

Particularly in the early phases after an incident, information is scarce, uncertain and evolves dynamically. Starting from an information perspective, there are three types of information that need to be combined to assess resilience in the context of a disaster:

- *Structural information:* relatively stable or only slowly evolving information, e.g., topography of a region, meteorology
- *Trends and developments:* information capturing meso-scale behaviour and predictable patterns such as economic growth, infrastructure capacity or migration;
- *Characteristic local information* capturing the direct and indirect impact of the hazard event

To assess how these different types of information affect disaster risk, Figure 1 gives an overview about the most important concepts we used. It shows that risk is characterized by the two dimensions *hazard* and *consequence.* The hazard describes the likelihood of an event and the exposure, which in the narrowest sense refers to the elements that are exposed to the hazard impact, comprising infrastructures, population and economy (Birkmann, 2007). These elements are *structural,* and relatively stable over time. Therefore, they can be assessed and modelled prior to an event.

To assess the *consequence*s of a hazard, it is important to consider the temporal dimension, the development of exposure during and after the hazard (Cardona, 2004). A flood stresses CIs for hours and days, whereas malicious attacks tend to last only for minutes. Similarly, disaster resilience does not only refer to a "bounce-back" capacity as it is understood in engineering (Bruneau et al., 2003; Reed, Kapur, & Christie, 2009). We acknowledge the fact that a crisis fundamentally changes the system, including technical components, preferences and critical needs. Response and recovery will naturally lead to a change of physical infrastructures and organizational processes and services within the wider socio-economic context. Therefore, we understand disaster resilience as a dynamic concept, closely linked to recovery processes.

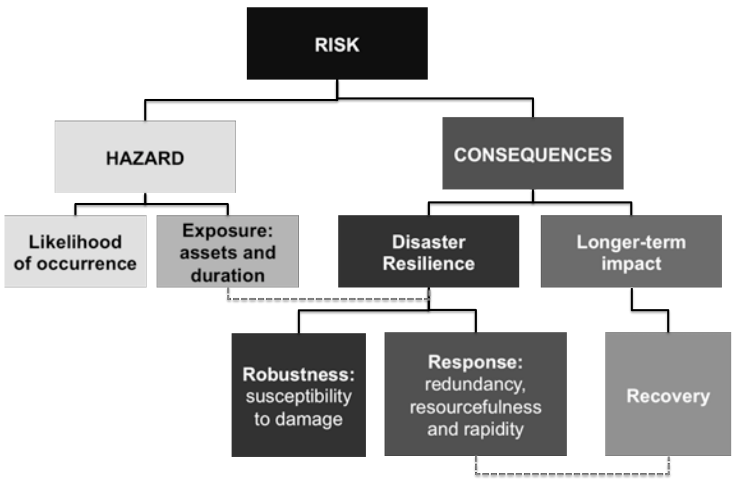


Figure 1: Conceptual model to assess disaster risk

Our results about the resilience of CIs for the use case follow the structure presented in Figure 1. We start with a quantitative analysis of the resilience of selected infrastructures. Subsequently, we provide a qualitative assessment of disruptions and consequences. This includes the identification of fragilities, e.g. critical components, critical geographic locations and interdependencies, the examination of recovery processes and the development of a general framework to assess resilience.

QUANTITATIVE RESILIENCE ASSESSMENT

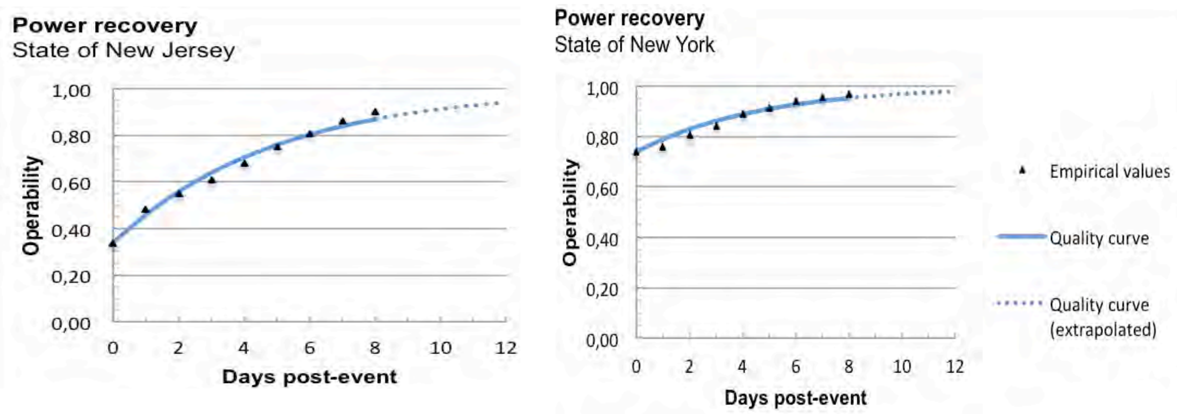
To understand and model resilience in engineering, quality functions that model the recovery of a system over time are widely used (Reed et al., 2009; Ulieru, 2007). In this section, we explore the results of this approach for individual infrastructures and interpret it in the light of its limitations. This approach is complemented by a qualitative framework, which is presented in the next section.

A system's quality or service level is modelled by $Q(t) = Q_\infty - (Q_\infty - Q_0)e^{-bt}$, where Q_∞ us the capacity of the fully functioning physical system, Q_0 the post-event capacity, b a parameter to model the recovery processes' speed. Instead of working with the initial state, Q_∞, we acknowledge the fact that the desired or satisfactory service level or physical state after an incident will have changed, and introduce a new variable, Q*, to model this target. This value Q* determines the convergence of the system, but is not stable itself. While in the first phases of response, realistic objectives will result in $Q^*(\text{response}) < Q_\infty$, the recovery ideally should result in better infrastructure systems in terms of robustness and capacity, hence $Q^*(\text{recovery}) > Q_\infty$. Note that recovery is here understood as a re-installation of technical capacity only; it should not be confused with the recovery of the wider socio-economic system.

The system operability at time *t* can be modelled by $Q_n(t) = 1 - \frac{Q_\infty - Q_0}{Q^*(t)} e^{-bt}$. High values of this ratio stand for high system disruption and low robustness. *Resilience R(t)* can be understood as the integral of this level of operability: $R(t) = \frac{\int_{t0}^{t} Q_n(t)dt}{(t-t_0)}$.

Quantitative Resilience Assessment for Electricity and Transportation

In our case study we calculate quality curves for the electrical grid and for New York subway system, and compare the results for this infrastructure with the resilience of the transportation system focussing on the similarities between different regions and infrastructures. To assess the dependence on electricity of a society that is characterised by a high degree of automation and, we chose the power infrastructure as one of the core CIs to investigate. The second CI we consider here is the transportation sector, due its importance for economy and its dependence on power (Merz, Hiete, Comes, & Schultmann, 2012).



$Q_{n,NJ}(t) = 1 - 0{,}662 * e^{-0{,}202*t}$ $Q_{n,NY}(t) = 1 - 0{,}261 * e^{-0{,}212*t}$

Figure 2: Power recovery: quality curves for the States of New Jersey (left) and New York (right)

Electricity Supply

The capacity of the fully functional structural system $Q\infty$ is represented by the total number of customers in the states of New York and New Jersey respectively (numbers according to EIA). This number is compared to a desired state of 98 % service level after the incident. All of the severely affected states had their peak power outage on the 30th of October 2012 (t0), the day after Sandy made landfall. All outage information for quality curves of the power grid was extracted from the Department of Energy Situation reports on Hurricane Sandy (Bryan, 2012a-c). The timeline for the quality curves is set from the 30th of October (peak outage, day 0) to the 8th of November (day 8). If there were several outage reports for one day the number of customers without service was averaged. Figure 2 shows a comparison of quality curves for the States New Jersey and New York.

MTA, NYC subway system

MTA provided outage maps[1] for the New York subway on in the aftermath of Sandy, from which the quality curves are derived for the New York subway restoration. MTA subway services were shut down by the 29th of October and remained shut until the 31st of October. On 1st of November, large parts of the network were re-opened, resulting in a jump of the operability, which is not related to reparation efforts. This is reflected by the rapidity of recovery as opposed to the power systems shown in Table 1, but we discounted it in the quality curves to refer to an increase of operability with respect to actual damages and disruptions, rather than in relation to preventive measures (see Figure 3)

For the subway system, we compared several desired recovery path. The blue curve shows the operability level as opposed to one stable aim of recovery, with $Q^*=Q_\infty$. The red curve acknowledges the fact that aims in the early response phase vary from recovery goals. Here, Q* varied over time, adapting the aim of an initial 75 % service level to the aim of 100 % service level after 3 days. Finally, the green curve shows illustrates the assumption of moving targets. From an initial aspiration level of 60 % recovery on (Q*(1)), we assumed that the aim was to open each day 30 more stations until 100 % service level is achieved. The almost stable curve for this case shows that this seems to correspond to what actually happened in the recovery for MTA. This analysis enables responding authorities to assess whether or not the recovery process meets their targets in terms of fixed goals or rates.

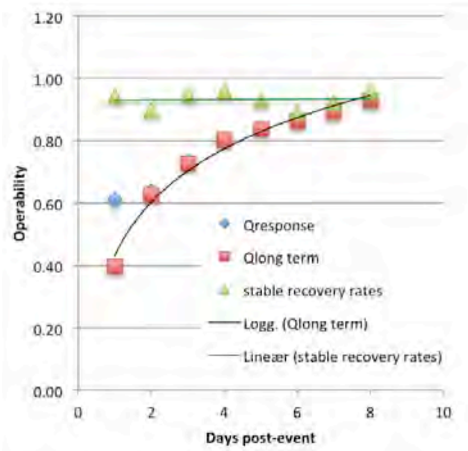


Figure 3: MTA, Recovery of the New York subway system

Cross Infrastructure Results and Discussion

Table 1 summarizes the results for the quality curves for different CIs. The power infrastructure in NJ experienced higher peak outage and is less resilient. This can, in part, be explained by the higher exposure (Sandy made landfall close to Atlantic City, NJ), but wind gust and inundations were similar on the NJ coast, NYC and Long Island (Mühr et al., 2012). Disruptions in the NYC power infrastructure were quickly restored and that overall resilience values were very high. An interesting observation is that the rapidity of recovery was similar, indicating a similar approach to recovery by emergency services and operators in both states.

Table 1: Results of the quantitative analysis for the power grid in NJ and NY and the NYC transportation network

		Power NJ	Power NY	Transportation: MTA NY
Robustness	$1-[(Q_\infty - Q_0)/Q^*]$	0.34	0.74	0.00
Rapidity	b	0.20	0.21	0.31
Resilience	R	0.67	0.87	0.67
SSE Quality Curve		0.004	0.003	0.096

Comparing operability of power and transportation systems show that the values of the subway system were lower than those of the State of NY power infrastructure during the selected recovery period. This indicates that subway services are dependent on electrical power and could not be restored before commercial power in the respective area was restored.

[1] Maps are available at: http://datanews.tumblr.com/post/35279442503/since-sandy-left-town-weve-been-downloading-mta, 2013-11-04

All functions and quality curves should be understood in relative terms: rather than providing absolute information, they enable decision-makers to compare the resilience of CIs across states or sectors in a quantitative way and integrate the temporal dimension (robustness vs. response, see Figure 1). In this sense, this model provides a specific lense, which contributes to the understanding of CI resilience from a distinct perspective. Other Important aspects of the non-technical dimension, such as the impact of disruption on population or economy, longer-term impact on recovery of markets or interdependencies between CIs are not considered in this model.

DISASTER RESILIENCE ACROSS CRITICAL INFRASTRUCTURES

In this section, we broaden our focus and analyse four infrastructures that are particularly relevant for emergency and healthcare services and tightly coupled: beyond electricity and transportation, we now also include oil and gas industry and the information and communication sector. Other CIs are not assessed in detail, but we provide an overview of the downstream consequences of disruptions. This choice enables us to consider CIs that are sufficiently different in terms of their physical and technical characteristics and the services provided e to outline differences between various types of CIs with respect to short and longer term consequences. This qualitative assessment aims at determining fragilities of those four CIs (critical components and locations) and to reveal interdependencies. In addition, we characterize the resilience of affected infrastructures, including expected longer-term impacts

Qualitative Assessment of Interdependencies

Electricity supply

The biggest fragilities of the electrical grid during Hurricane Sandy were the transmission and distribution components (Bryan, 2012c). Strom winds had downed and disrupted overhead power lines and it substantial effort of emergency services to rebuild them (NHC, 2012). Flooding affected dozens of substations, among the most severely affect were Public Service Electric and Gas (PSEG, NJ) and Long Island Power Authority (LIPA). PSEG reported that *excessive flooding created by the storm surge affected a large number of substations* (Bryan, 2012a). Damage assessment and replacement of equipment could only start when the waters had receded (Bryan, 2012b). Similarly, LIPA facilities were affected by flooding and high wind gusts, resulting in damaged substations and downed lines. Moreover, roads were closed due to flooding or debris and sites were inaccessible for repair crews (Bryan, 2012a). The power plant infrastructure experienced some outages but since the transmission network was down, the functioning of the plants was not critical at this stage to supply customers, but required to maintain grid stability.

Long-term recovery was a local issue that affected small regions or specific sites. Thus a collection of relevant snapshots helps us to get an idea of the problems. In flooded regions, for example on barrier islands along the shore, electrical equipment had to be replaced due to saltwater damage. On the Rockaways, 10 % of the residents were still without power 5 months after Sandy (Mosbergen, 2013). In the hardest hit spots on the coastline, recovery processes lasted for months.

Oil and Gas Industry

Due to its harbour and terminal infrastructure, the oil and gas supply chain is particularly prone to storm surges. At the same time it is greatly dependent on secure power supply. Due to power outages, infrastructures such as pipelines, oil terminals, storage tanks and filling stations could hardly function. For instance, Colonial Pipeline shut its northeast mainline serving NJ, NY and PA harbour markets on the evening of the 29th of October (Bryan, 2012a) because of expected power outages. Only a small number of installations remained operational that had access to backup power systems. Table 2 provides an overview of affected refineries according to (Bryan 2012a-c, Schneyer & Gebrekidan, 2012; Zernike, 2012).

Although the supply side faced some critical outages during Hurricane Sandy, delivery bottlenecks were more harmful. Equipping more critical oil terminals and filling stations with backup generators could help to reduce this problem. Emergency service infrastructure was less affected by gas shortages since they could rely on government resources. In general, no long-term recovery problems considering oil and gas infrastructure were reported. The disruptions in oil and gas infrastructure, especially the gasoline shortage, led to interdependencies with transportation and backup power grid.

Table 2: Overview of refinery disruptions due to power outages in the aftermath of Sandy

Refinery	**Location**	**Capacity (barrels/day)**	**Status as of 1:00 p.m. EDT 2012/10/29 (peak disruption)**
Hess	Port Reading, NJ	70,000	Shut down
Monroe Energy	Trainer, PA	185,000	Reduced Runs
PBF Energy	Delaware City, DE	182,200	Reduced Runs
PBF Energy	Paulsboro, NJ	160,000	Reduced Runs
PA Energy Solutions	Philadelphia, PA	335,000	Reduced Runs
Phillips 66	Linden, NJ	238,000	Shut down

Information and Communication infrastructure

According to the Federal Commission for Communications about 25 % of customers in regions affected by did not have cellphone, landline, broadband Internet and cable TV connections (Genachowski, 2013). The main reasons for outages of mobile communication were loss of power, flooding, loss of cell-site backhaul connections, lack of site access and damaging debris. Considering the ICT infrastructure there were two major issues: flooding and power dependence. Saltwater damage of cable vaults and other cable structures forced providers to replace equipment. Internet outages were related to the loss of commercial power, disruptions in data centres and damages in the cable network, but, in general, Internet infrastructure suffered no wider outages. Although mobile communication was hit with considerable outages, parts of the grid could be relatively quickly replaced by using of mobile trailers.

Transportation

Transportation infrastructures combine different physical components (such as airports, tunnels, bridges or roads) and services (for example subway, bus or train service). The most critical event concerning the transportation infrastructure was the inundation of the New York Metropolitan Transit Authority (MTA) East River subway tunnels, leaving millions of commuters stranded for several days. In addition, the destruction of MTA's Rockaway line required intensive long-term recovery work. Saltwater damage of equipment and the removal of debris that remained on tracks and roads after the water receded prolonged the restoration efforts. Blocked or destroyed roads also led to interdependencies with other infrastructures. In addition, the NJ Transit locomotive fleet was severely damaged by flooding.

Considering interdependencies, transportation infrastructure was mainly affected through cascading failures as it relies on commercial power, oil and gas supply and functioning ICT systems. At the same time, cascading effects prolonged restoration efforts: blocked roads or lack of site access prolonged repair efforts especially in the power and ICT infrastructure.

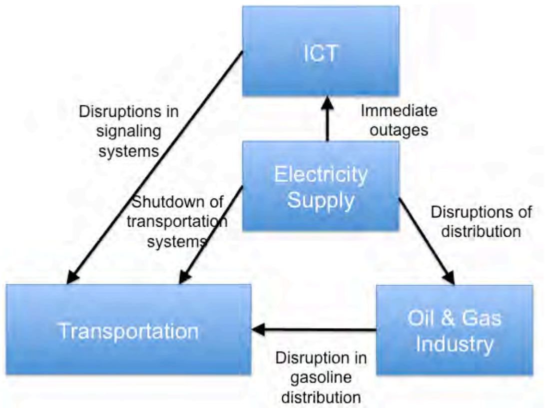


Figure 4: Short Term Consequences of CI Failures for Selected Sectors

Cross Infrastructure Results and Discussion

The supply of electricity is a central node in the system of CIs as shown in Figure 4, which summarizes the most important short-term consequences. Disruption of electricity supply not only hampered other systems and economic sectors to function, it also made emergency management more difficult: disruptions in the grid propagated to other infrastructures as cascading failures leading to immediate outages of transportation services, gasoline distribution and ICT systems due to tight coupling.

As time passed, also indirect and longer term impacts, as shown in Figure 5 became more and more important. Oil and gas industries suffered severe outages due to the loss of commercial power through cascading failures. Backup power was only of minor help and could not prevent disruptions in gasoline distribution. This he bottleneck led to further outages in backup power, which then brought cascading failures to further infrastructures. The interdependency of oil and gas and power infrastructure was among the most critical interdependencies due to its downstream consequences. Transportation services were also affected because of their dependency on gasoline supply. When considering ICT infrastructure, no direct dependency or interdependency effects were reported.

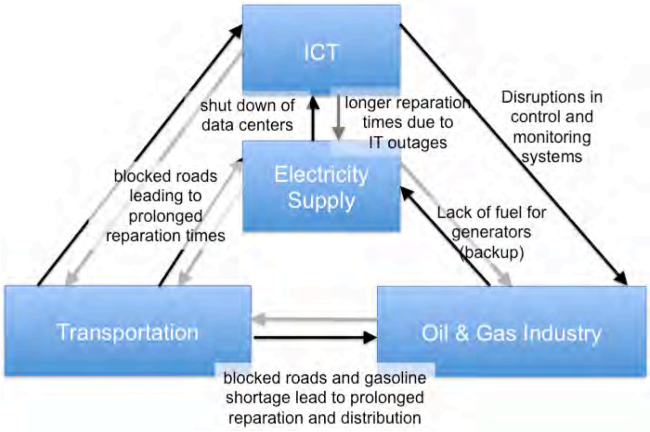


Figure 5: Cascading effects and reinforcing loops of CI disruptions

ICT infrastructure is heavily dependent on commercial power and was affected by cascading failures. In one case, it was also affected by oil and gas outages through a n^{th}-order interdependency, but this was no general problem. On the other side, operation of power infrastructure and transportation services depends on functioning ICT infrastructure. In summary, ICT shows no direct connection to oil and gas infrastructure. In most cases, power disruptions were the root of outages in other infrastructures. Increasing resilience of the power grid should therefore be prioritized, and critical components in power-dependent infrastructures should be made more resilient against power outages, for instance by installation of backup power systems.

CONCLUSIONS AND OUTLOOK

Hurricane Sandy's storm centre hit some of the most densely populated States of the US, which are of major importance for the national and global economy. A prerequisite for economic growth and societal welfare are functioning complex critical infrastructure (CI) systems that are required to meet the demand of power, oil and gas, ICT, transportation and water. To manage and mitigate risks to these infrastructures, the potentially affected communities, and economic prosperity, policy makers, CI providers and decision makers at regional level have started to focus on improving disaster resilience instead of mitigating individual hazards.

Still, resilience is an abstract concept, and frameworks are required to enable measuring and comparing resilience of individual CIs and across different infrastructures. Moreover, it is important to consider resilience in a given context; the concept needs to reflect the phase of disaster response, geographic location, drivers, values and norms. Rather than defining a unique measure for resilience, this paper defines an approach to measuring disaster resilience that can be applied in different settings.

To demonstrate this approach, this paper analysed the impact of Hurricane Sandy on tightly coupled infrastructure systems and investigated their resilience. The infrastructure systems in the Sandy-affected states are heavily dependent on electrical power. The power grid itself is highly vulnerable to hurricane-related hazards, e.g. high wind gusts and storm surges. Moreover, cascading effects due to power disruptions were severe. With an increasingly close link between electricity and ICTs, in future an even tighter coupling between those systems, leading to more sever disruptions can be expected.

To measure resilience in context, local information needed to be integrated from a plethora of different sources. The studies and analyses presented in this paper were carried out remotely, and therefore we had only limited access to local communities, responders and CI providers. We focussed on official information sources and media reports that were by their nature disconnected from community endeavours (often vulnerable groups) and the current may induce selection bias. To avoid this bias, or better describe and capture the very nature of it, a framework is required that enables comparing, assessing and integrating information from sources as different as official reports, interviews, social media and newspaper reports. This also implies that the links between experts, practitioners, and responders onsite and scientists and volunteers working remotely need to be strengthened, and new concepts for remote support need to be developed.

To provide decision support in near real-time, analyses and results need to be tailored to address the respective decision-makers' needs. To this aim, GIS and mapping tools can be very useful to highlight hotspots and to provide information about the resilience of critical infrastructures. Any tool or technology needs to respect and reflect the realities of the field and carefully balance the possibilities of analyses or visualisations with capacity and bandwidth, or even just time available on the field.

Disaster resilience should be understood as a concept that embraces the aims of a community or society. In this paper, we focussed on understanding the impact of different desired paths on the quality curves that model the desired level of operability. Yet, this approach remains to be tested with decision-makers in practice. On the level of modelling, future work consists in extending this framework to integrate more infrastructures, modelling the interdependencies between them, and test the results with decision-makers in practice to derive valid recommendations for recovery and reconstruction.

On a broader level, critical infrastructures can be understood as providing vital functions, about which there is a societal consensus that they need to be maintained. In this paper, we have outlined that a disaster will affect the aims, and what is perceived as most urgent or critical will vary (i) between different actors and authorities and (ii) as the situation evolves from response and relief to recovery. This means that the needs are *not* independent from the aid. This relation understanding disaster resilience not only at a community or sectorial level, but embedded in the context of humanitarian aid requires further research.

ACKNOWLEDGMENTS

We thank our colleagues from the Karlsruhe Institute of Technology (KIT) for the discussions on critical infrastructure resilience. Furthermore, we are grateful to the team of the Disaster Resilience Lab and its supporters for inspiring work connecting research and the practice of disaster response.

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