Enhanced Crisis-Preparation of Critical Infrastructures through a Participatory Qualitative-Quantitative Interdependency Analysis Approach

Axel Dierich
inter 3 Institute for Resource Management
dierich@inter3.de

Katerina Tzavella
Technische Hochschule Köln
katerina.tzavella@th-koeln.de

Neysa Jacqueline Setiadi
Technische Hochschule Köln
neysajacqueline@yahoo.com

Alexander Fekete
Technische Hochschule Köln
alexander.fekete@th-koeln.de

Florian Neisser
Technische Hochschule Köln
florian.neisser@th-koeln.de

ABSTRACT

Critical Infrastructure (CI) failures are aggravated by cascading effects due to interdependencies between different infrastructure systems and with emergency management. Findings of the German, BMBF-funded research project "CIRMin" highlight needs for concrete assessments of such interdependencies. Driven by challenges of limited data and knowledge accessibility, the developed approach integrates qualitative information from expert interviews and discussions with quantitative, place-based analyses in three selected German cities and an adjacent county.

This paper particularly discusses how the mixed methods approach has been operationalized. Based on anonymized findings, it provides a comprehensive guidance to interdependency analysis, from survey and categorization of system elements and interrelations, their possible mutual impacts, to zooming into selected dependencies through GIS mapping. This facilitates reliably assessing the need for maintenance of critical functionalities in crisis situations, available resources, auxiliary powers, and optimization of response time.

Keywords:

Critical Infrastructure Protection, Interdependency, Resilience, Vulnerability, Cascading Effects, Emergency Management, Participatory Approach

INTRODUCTION

To build up resilience of Critical Infrastructures (CI), infrastructure operators, public crisis managers and emergency responders need to get a joint understanding of the entire system of systems. With automation, digitalization and efficiency gains, CI systems become increasingly complex, and so do their interdependencies. Preemptive risk management, as well as ad-hoc crisis response therefore need to consider this interconnectedness (Rinaldi et al., 2001; Little, 2002; O´Rourke, 2007; Lenz, 2009; Utne et al., 2011; Ouyang, 2014). As Georgios Giannopoulos of the Joint Research Centre of the European Commission puts it, „a resilience analysis requires assessing the infrastructure from a holistic point of view, enhancing coordination and timely response throughout the interdependencies" (Giannopoulos et al., 2012, p. 38). Hence, risks can „be tackled by increasing the capacity of the dependent nodes to withstand the perturbation" (ibid.).

However, there is a general tendency among infrastructure operators to focus merely on their own systems – resulting in little exchange of information to identify the overall connectedness (Bach et al., 2013). As Grafenauer et al. (2018) have put it: "As systems become more complex, a clear overview on the consequences of a problem is harder to obtain". An insufficient understanding of the dynamics of interdependencies and of the dynamics of their interplay however may result in ineffective response and poor coordination between decision makers and disaster managers before, during and after a disaster (Baloye & Palamuleni, 2016; Faturechi & Miller-Hooks, 2015), which can lead to serious delays in emergency service delivery.

These aspects were the key motivation for performing a qualitative interdependency and impact analysis in the "Critical Infrastructures Resilience as a Minimum Supply Concept" (CIRMin) research project, running from June 2016 to May 2019. It aims at strengthening the (joint) preparedness and coping capacity of Critical Infrastructures in Germany, in order to optimize minimal supply for the population in case of CI break-downs. A reliable information basis for decision-making (Clarke, 1999; Heinecke, 2006; Weimer-Jehle 2015) was created through a thorough system analysis, involving all relevant actors and thus taking inter- and trans-sectoral dynamics of the systems' functioning into consideration (López-Silva et al., 2015; Schätter et al., 2014; Reissberg, 2012; Giannopoulos et al., 2012). It was accompanied by an open-data-based GIS spatial analysis and visualization which supported the analytical documentations of key sensitivities, weak spots and demands.

The CIRMin approach was mainly build on a personal exchange of information among experts and with the researchers. Emergency response, electricity and water supply have been selected as focal sectors, according to their relevance for civil security in Germany. Through bringing experts from those and further CI sectors together prior to hazard events, it was intended to provide them with a clearer and focused understanding of interlinkages and dependencies between their different infrastructure sectors and thus to jointly enhance resilience building.

As case studies, three municipalities (in Western Germany, Land of North Rhine-Westphalia) have been selected since this administrative level bears first responsibility for crisis management in Germany. In order to enable studies on differences and similarities, a metropole city, its neighboring, mixed rural/peri-urban district and another major city were selected.

RESEARCH GAP

The literature review related to CI interdependencies and methodological approaches included scientific publications, grey literature such as guidelines or technical reports and reports on previous or ongoing German and EU research projects. The following subchapters provide an overview of different approaches to interdependency analysis as well as a conceptual basis for the performed GIS analysis.

Methodological Approaches to Assessing CI interdependency

Most approaches of interdependency analysis attempt some kind of quantitative modelling (See e.g. Kröger, 2012; Pederson et al., 2006; Bloomfield et al., 2009; Ouyang, 2014; Dudenhoeffer & Permann, 2006; Hokstad et al., 2012). However, as Ouyang (2014) puts it in an overview, most approaches need medium to large quantities of input data with often difficult data accessibility. Also reviews from Bloomfield et al. (2009) and Pederson et al. (2006) discuss the challenges of data requirements, finding data sets and providing realistic demonstrations. It is often difficult to capture the potential sectoral and intersectoral cascading effects of supply breakdowns of critical sectors such as electricity and water in their complexity. On the other side, most purely quantitative data analyses have been limited to modeling systems in a near-realistic sense that did not sufficiently reflect the complex and often tight coupling, factors of human behavior and thus, hidden logics of CI systems (see e.g. Perrow, 1984). Also, security concerns of misuse by attackers and data sensitivity concerns are major constraints to information sharing. Bloomfield et al. (2009) therefore propose qualitative approaches that involve different stakeholder groups at least as a preliminary step.

Another challenge in research projects so far seemed to be consequently applying an intersectoral approach: Various research projects like MICIE[i], AFTER[ii], TankNotStrom[iii], MIA[iv], STREST[v], Smart Resilience[vi], NoWa II[vii], KontiKat[viii] and studies such as the TAB Report (Petermann et al., 2010) successfully tackled the above-described challenges of information exchange. But these projects so far only analyzed unidirectional dependencies from single CI sectors, yet no holistic interdependency assessments. The projects Casceff[ix], Predict[x], DRIVER[xi], and Crisma[xii] developed practical tools with a high involvement of practitioners, to assess possible impacts of incidents to (inter)dependent systems at a higher abstraction level, i.e. systems of infrastructure sectors and their services. They thus demonstrated the importance of actively involving the practitioners from various sectors in development of interdependent infrastructure models. But still, this research mainly relied on or was limited to one or two CI systems (Barthe-Delanoë et al., 2015). Broadening the scope of application of these data bases to the entire system of systems of Critical Infrastructures and crisis management would make them hardly manageable. This "requires extensive knowledge" about a metropolitan area, "including e.g. building inventory, systems, and suitable data to characterize the employed hazard models" (Garcia-Aristizabal et al., 2015, p. 9).

Projects at the European level with an intersectoral approach (such as the Snowball[xiii] project and Fortress[xiv]) have developed computer simulations of various supply sectors. They provided a very far-reaching approach to viewing infrastructures in their vast complexity as socio-technological systems. Their developed models are user-centric by involving actively the practitioners and match demands on modern CI resilience approaches (Bach et al., 2013). But in turn, these elaborate processes rely on vast data sets about a handful of very specific impact scenarios. As an approach to identifying the key needs for action to prepare a city or region for different kinds of CI outages, they seem to be too costly and not easy to handle.

Use of GIS Analysis

The development of spatial technologies has been driven by needs for better, easier (Mansor et al., 2004) and quicker decision-making for emergency response, and for the overall resilience building (GAR, 2015). Many of the critical problems that arise with extreme events such as floods or earthquakes are inherently spatial, e.g. the extent of the disaster, on-site crises and number of people in need (Tzavella et al., 2017).

GIS are useful for emergency management by visually displaying key information before and most importantly during an emergency event (Fekete et al., 2016; Tzavella et al., 2017). In CIRMin, information about disaster impacts on a system were integrated with emergency operations capability (Petit et. al., 2015), to better understand and anticipate the consequences of an incident and to support incident management activities (cf. Petit et al., 2014). Specifically, GIS have been recognized as useful tools to determine the changes in impact on a geographic area (Robert et. al., 2015).

Scientific advances in utilizing spatial information are demanded in the areas of CI asset mapping, adding additional context information, such as technical susceptibility of system components or social vulnerability of the supplied population (Fekete, 2012a). However, such exposure assessments are not sufficient to capture effects outside of the initial damage area (such as the flood-zone), which is typical for interdependent and network type of CI services such as electricity grids (Fekete, et al. 2017). Spatially explicit interdependency assessments between CIs reaching beyond e.g. unidirectional dependencies from resources or impacts, are still lacking for Germany.

CONCEPTUAL BASIS OF THE APPROACH

Definition of CI

Critical Infrastructures are defined differently, while overlapping in stressing vital or essential infrastructure elements and processes from the viewpoint of a (mostly national) government perspective (US Government, 1996; European Commission, 2008, FMIG, 2009). In Germany, CI are defined by importance to the state if their failure can cause major damages or destabilization of public order (FMIG, 2009). For this study, this definition of Critical Infrastructures is used: "*organizational and physical structures and facilities of such vital importance to a nation's society and economy that their failure or degradation would result in sustained supply shortages, significant disruption of public safety and security, or other dramatic consequences" (*FMIG, 2009, p.3).
The CI in Germany include nine sectors and selected branches (FMIG, 2009), wherein water supply, electricity supply, and emergency response, which are the focus of the study, are listed.

Types of Interdependency

Rinaldi et al. (2001) define connections between infrastructures as unidirectional (dependency) or bidirectional (interdependency). Within the view of complex systems, many infrastructures are connected one way or another, directly and indirectly with each other, so that it is necessary to assess the interdependency in a holistic and systemic way. Interdependent infrastructures also display a wide range of spatial, temporal, operational, and organizational characteristics, which can affect their ability to adapt to changing system conditions (Rinaldi et al., 2001).

In this paper, the dimensions of interdependency used are based on the interdependency concepts from Rinaldi et al. (2001; also: Turoff et al., 2014):

- i) Physical interdependency: the state of each is dependent on the material outputs of the other
- ii) Informational interdependency[1]: the state of an infrastructure depends on information transmitted through the information infrastructure
- iii) Geographic interdependency**:** a local environmental event can create state changes in several infrastructures
- iv) Logical interdependency: social and political processes

Conceptual Principals

The resilience of complex systems of CI can be observed using a systemic and biocybernetic lens, regarding infrastructures as dynamic and to a large degree self-steering systems. Here, Vester (1988; 1991; 2012) describes biocybernetic systems as examples for self-contained – and in a sense resilient – systems and sub-systems, which use a set of rules that make them function in an optimal way. Projecting these examples from nature on water, electricity or gas supply, transportation, ICT, emergency response and so on, helps in understanding the dynamics, the existing connections and possible interactions within and between the systems and thus the overall complexity of critical infrastructures.

For the interdependency analysis, the Vester (1991; 2012; see also Wilms, 2006) approach of system and sensitivity analysis for complex systems, as adapted by Dierich et al. (2012) (see also inter 3, 2013) to the specific context of interdependent critical infrastructure systems, has been applied. The method was advanced by integrating the concepts by Rinaldi et al. (2001) for systematic classification of interdependencies and Bagheri & Ghorbani (2008) for capturing the variability and dynamic behavior of the complex systems based on a five dimensions model framework.

METHODOLOGICAL APPROACH

The methodological activities in CIRMin took the above described state of the art into consideration to develop the mixed qualitative-quantitative approach of analyzing and mapping the interdependencies between various infrastructure sectors at manageable effort and for crisis situations in general. Employing "Fuzzy Logic" (Vester, 2012; Malik Management Zentrum, 2014) by means of reducing the information depth of the analysis of systems and their elements, the method described in the following was deemed appropriate to solve the above-mentioned handicap of purely data-based decision-support systems.

Sources for data

The basis for the study was the engagement of representatives from CI operators and other project partners from city, regional and national administration. For each case study, representatives from relevant operating companies (electricity supply grid operators, transmission grid operators, water suppliers, wastewater and flooding management and ICT operators) were involved, as well as municipal disaster management officials and emergency responders.

[1] There is a slight adjustment to the concept of Rinaldi et al. in this study, as 'informational interdependency' was used instead of 'cyber interdependency'. Rinaldi et al actually defined it in a wider sense as the dependency on information flow or exchange taking into consideration the actors involved, and as the information and communication technology used. For the study, we deemed communication and exchange of information among actors an important focus, and therefore use the widened term of 'informational interdependency' as defined above.

Qualitative and quantitative analyses have been conducted in parallel with each other. For gathering the qualitative information, semi-structured interviews and moderated focus group discussions in expert workshops served as primary data source. In total, 18 detailed (2-3 hours) interviews with in each case 1-3 participating stakeholders, as well as further telephone interviews have been conducted. Uncertainties have been minimized by comparison of expert views and their dialogic validation. Six expert workshops involving each 10-15 stakeholders and about 10 researchers took place at decisive points of each methodological step and served to discuss findings, jointly draw conclusions from them and perform key analytical steps such as the Cross-Impact-Analysis. Their structure varied from focused discussion to intense co-working. Participants slightly varied but at least the focal CI units and agencies as mentioned above were always represented - with one exception when operators from another region in Germany were brought together to evaluate the transferability of the findings of the interdependency analysis.

Quantitative analysis using GIS applications has been based mainly on available open-source (OS data) and authoritative ('official') data, and its results have been verified by the experts in an iterative process. The advantage of using OS data or even data that is produced voluntarily on-site by the people in need is that it is the most up-to-date data that the emergency responders can have at hand before and specifically during a crisis (however, always depending on the type of crisis) (Tzavella et al., 2017). For this study, before providing findings to local authorities and to the public, they needed to be screened and selected according to security and data sensitivity demands. This integrative and joint process provides new empirical and expert-verified information and at the same time further strengthens collaboration and information exchange among CI and emergency management actors.

Qualitative Interdependency Analysis Steps

Following the concepts discussed previously, the chosen approach to system analysis incorporated the identification and description of critical infrastructure elements and (inter)dependencies in a holistic picture. Different types of systemic elements have been distinguished for the analysis of the systems, together with relational processes and interdependencies. As a further step, through the sensitivity analysis according to Vester (1991; 2012), the identified system elements were aggregated - again with intensive participation of the CI stakeholders - to impact factors and juxtaposed in a cross-impact-matrix to assess their reactivity and dynamic character. The relevant stakeholders were brought together in a workshop, in order to agree on the definition of a limited number of impact factors and discuss and value their interdependencies.

Through reducing their overall complexity, a complete overview of the interwoven CI systems was to be achieved; however, zooming into them and finding accurate and reliable information about particular elements and relationships should remain possible. In both system analysis and discussion of the sensitivity of the systems, the linkages were considered more important than the singular assets, technologies, actions, etc. Therefore, structures and processes were considered in an integrated way.

Quantitative Analysis

The main idea of linking quantitative GIS analysis to the qualitative interdependency analysis was to use the capabilities of GIS in terms of i) visualizing and pinpointing focal interdependencies in a detailed manner and ii) further analyzing, verifying and complementing the gained information. In the opposite sense, the GIS analysis also examined the qualitative results for needs of further detailed analysis.

Data was processed through the Extract-Transform-Load (ETL) method[xv], also to allow for data interoperability. In order to simplify and semi-automate the processes, spatial ETL tools were used[2], for e.g.:

- Filtering attributes and merging them with other feature classes
- Using attribute values to create unique feature classes on the fly

[2] Spatial ETL tools are user-created geoprocessing tools that can transform data between different data models and different file formats. These tools are capable of a wide range of processes and data flows, from simple format translations to complex transformations, which restructure geometry and attributes. They can be used as stand-alone geoprocessing tools or run as part of a Python script tool (see https://pro.arcgis.com/en/pro-app/help/data/data-interoperability/spatial-etl-tools.htm).

- Separating data using test criteria
- Creating line features from coordinate values.

Collected data from different sources has been integrated in an ArcGIS environment. Specifically, available OS geodata have been utilized stemming from projects such as OpenStreetMap, provided and maintained by the community of Geofabrik[xvi], the city of Cologne[xvii] and the international commission of the Rhine[xviii] on actual damages, flood extent, etc. The flood extent for the area of Cologne was downloaded from the Rhine Atlas (IKSR, 2001; Rhine Atlas 2015).

After the initial spatial assessments and GIS visualisations, results and some conclusions were presented to the experts so to verify them. The quantitative research has deliberately been designed as an iterative process of building a joint knowledge basis for CI protection and emergency management. Such participatory GIS approaches have already been applied in other thematic areas (e.g. Pfeffer et al., 2011; Brennan-Horley & Gibson, 2009; Kwan & Knigge, 2006)

DATA ANALYSIS AND EXEMPLARY RESULTS

The following section shows how the interdependency analysis can be performed in four analytical steps and presents some anonymized and generalized results that are based on the actual results from the case studies[3]. For the quantitative (GIS) analysis, maps containing non-sensitive information and using open source data are presented for the city of Cologne.

The following analytical steps have been conducted:

1. identifying and categorizing key CI processes and elements;
2. analyzing interdependencies between elements within and across sectors;
3. cross-impact-analysis: clustering of elements to impact factors and valuing impacts;
4. combining the qualitative analysis results with quantitative (GIS) analysis.

Key CI Processes and Elements

Interviews and discussions with the infrastructure operators and emergency responders in the case study areas provided a thorough understanding of i) processes and elements which are important to deliver the respective services to the community, and ii) interdependency linkages with other infrastructures. Given information was questioned during the interviews with regard to possible supply outage scenarios. The following Table 1 provides a few generalized processes and associated elements - out of the hundreds identified - that applied to all four case studies.

[3] The actual results cannot be made public in detail, in order to respect confidentiality and sensitivity of the data. Selected findings have been slightly altered and thus anonymized, to be able to exemplarily show them in this paper.

Table 1: Selected examples of described processes and elements (Source: own table)

Example	Infrastructure	Process	Element(s)	Qualitative description
1	electricity supply	supply distribution	supply network and supply sub-station	network structure, supply areas, existing redundancies
2	water supply	network regulation and repair management	control center, which is linked with alert service	main point for information flow and contact with other responsible divisions as well as repair works during supply breakdowns, communication media
3	water supply	repair management	on-call duty and repairing vehicles	cooperation with external sources, capacity and repairing time
4	water supply	repair management	switching the distribution network system	network structure (redundancies), automatic or manual, estimated switching time
5	emergency response	emergency operation	operation leader	procedure in operation and decision making, cooperation with other actors

To analyze and evaluate the systems and processes graphically, elements were categorized as follows:

- actors (depicted as squares)
- technological processes and facilities (depicted as circles)
- resources (depicted as hexagons)
- measures (depicted as arrow-like hexagons)
- environmental conditions (depicted as rhombuses) and
- entire infrastructure systems (depicted as octagons).

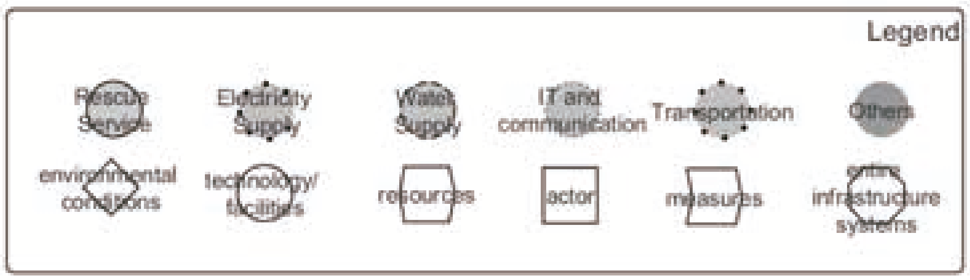


Figure 1: Categorization of elements

Interdependencies Between Elements Within and Across Sectors

As previously mentioned, the interdependencies between elements were categorized as physical, informational geographical, and logical interdependencies. Technical and informational interdependencies clearly prevailed over geographical and logical ones. Exemplary interdependencies are listed in Table 2:

Table 2: Selected interdependencies based on interdependency dimensions adapted from Rinaldi et al. (2001) (Source: own table)

Sub-process	**Interdependencies**			
	physical	**informational**	**geographical**	**logical**
Notification of disruption and mobilizing resources	Electricity supply of control center, electricity supply of IT system and communication media	Mobilizing resources for (manual) repairing activities Contact with fire brigade	In case of unavailable (public) ICT: distance to person/location (for e.g. courier)	Legal priority of public communication service in case of disruption
Repairing activities	Electricity supply, transportation network, fuel supply, supply with spare parts, external service firms (e.g. civil engineering)	Information exchange between control center, repairing personnel, other actors (fire brigade and police forces, crisis unit)	Accessing the affected areas, proximity to other mains, assets and supply pipes/lines	Existing contract with external service firms, prioritization
Dispatching of emergency responders and vehicles/ engines	Electricity, water, heat and food supply of fire brigade control center Fuel supply of vehicles	In case of electricity cuts: Information about their severity, information about CI (location, capacity of existing emergency power generators)	Distances, traffic, road conditions, degree and spatial extension of population/ CIs affected	Prioritization of emergency operations

As an overview, all interdependencies found in a case study have also been depicted graphically, as shown exemplarily in Figure 2.

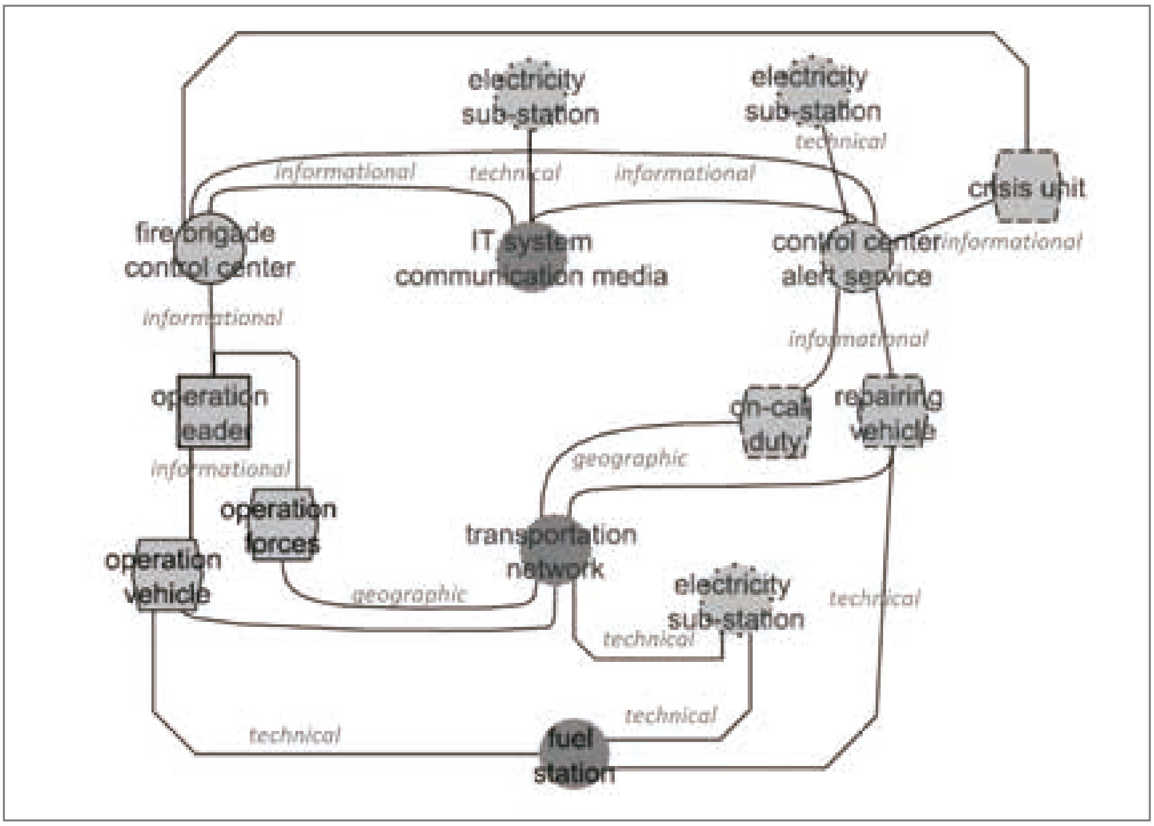


Figure 2: Visualization of the exemplary processes, elements and their interdependencies (Source: own figure)

In the simplified sub-system (Figure 2), information about any disruptions in day-to-day operation through the remote monitoring system or through notification by the customers is collected at the control center, which will in turn notify the repairing service or, in major events, the crisis management unit. The repairing service mobilizes its resources (vehicles with on-call duty) using available communication devices, and the repairing time would depend on the capacity and location of these resources, as well as on the traffic and street/road conditions (transportation network) on the way to the affected location. The service vehicles also rely on supply of fuel at petrol stations, which in turn rely on electricity. In case of a more severe supply disruption, contacts will be established, and information will be exchanged between the control center of the water supply operator and the control center of the emergency responder (fire brigade) for preparing possible operations. On the other hand, the functionalities of the control center depend on electricity supply from electricity substations (although with redundancies in the supply network and own emergency power generation capacities).

This example only shows a small part of the analysis. The whole system analysis at the end would look more complex, as exemplarily shown in Figure 3.

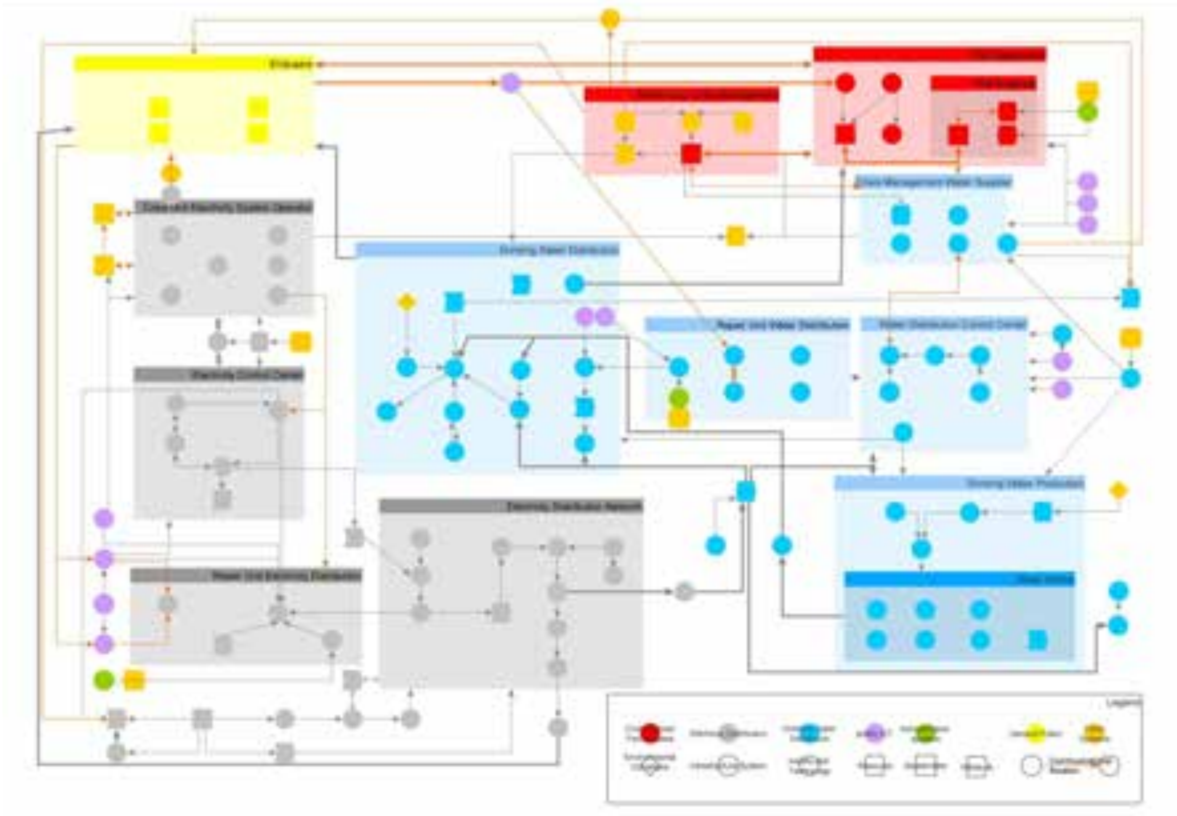


Figure 3: Schematic visualization of the processes, elements and their interdependencies in an anonymized city (Source: own figure)

Cross-Impact-Analysis: Procedure and Results

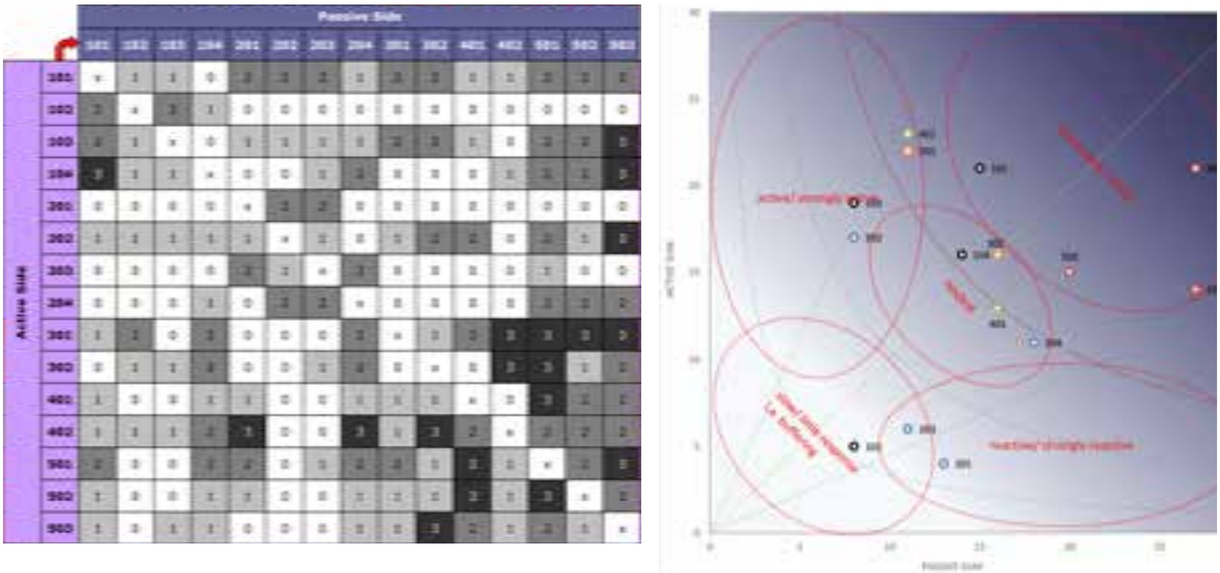
The compilation of the elements of the CI systems documents their structure and immanent processes, as well as interlinkages with each other. However, it does not help in understanding their dynamics, including their reactivity to major disturbing events and cuts in supply or information relationships. Possible cascading effects can only be assessed through a sensitivity/ cross-impact-analysis (CIA), as briefly explained above (see also (Vester, 2012; Weimer-Jehle, 2015; Heinecke, 2006). This can most practically be done by a matrix that juxtaposes system elements of the different CIs (Wilms 2006; Vester, 1991, 2012). However, as it was impossible to juxtapose each of the roughly two hundred elements (per case study) with each other, a clustering to so called "impact factors" was needed. These constitute kind of larger functional units within the systems and may embrace an entire system (such as the factors "ICT" or "flood control", see below) or even various systems (such as the factor "transportation network/ traffic"). Each of the 15 factors was defined precisely by listing up all assigned elements. This clustering allows reducing the total systemic complexity and hence gives a complete overview of the considered interdependent CI systems in the respective area/city. It visualizes the 'system of systems'.

Assessing the impacts between the factors of the different CI sectors in "Cross-Impact-Matrices" followed certain rules (see Figure 4, to the left, compare Wilms 2006; Vester, 1991, 2012):

- Both defining the factors and impact assessment was done in a workshop, involving stakeholders from the concerned CI sectors, who were divided into three groups according to the three case studies. For all three different case studies, uniform impact factors were created; however, in another context, other factors might be selected and defined.
- The assessment was done under the overarching question: "What impact does a serious disturbance of the functioning of a factor have on the other factors?" The effect partly varied according to changing focus on the different elements contained in a factor. As risk analysis needs to take into account any probabilities, these have explicitly not been assessed; unlike in the original and still vastly applied CIA

approach of Gordon, Hayward (1968), Enzer (1972) and Helmer (1983) (see also Kosow & Gaßner, 2008; Weimer-Jehle, 2015; Heinecke, 2006). However, implausible effects have been ignored.

- The assessment of impact strength was done on a scale 0 = no or very low impact/ no relation, 1 = impact underproportionate/ lower than disturbance, 2 = proportionate impact, 3 = impact overproportionate/ higher than disturbance.
- Only direct impacts were considered. For example, a problem in water extraction impacted on water distribution and this in turn on the end users.
- Participants were first asked to individually assess the impacts. The reasoning behind was then explained, discussed and documented, and each impact strength was decided in a consensual manner.



1 Impact Factors Electricity Supply
- 101 Electricity Distribution
- 102 Grid Control and Monitoring
- 103 Grid Recovery after Blackout
- 104 Repair Management, Crisis Management, Crisis Communication

2 Impact Factors Water Supply
- 201 Water Extraction and Monitoring
- 202 Water Distribution (Network)
- 203 Distribution Network Control and Monitoring,
- 204 Repair Management, Crisis Management, Crisis Communication

3 Impact Factors Public ICT and Traffic
- 301 Public ICT
- 302 Transportation Network/ Traffic

4 Impact Factors Water Disposal and Flood Control
- 401 Communal Wastewater Disposal
- 402 Flood Control

5 Impact Factors Emergency Services/ Population
- 501 Operative Tactical Crisis Management/ Emergency Responders
- 502 Administrative Organisational Crisis Management
- 503 Demands and Commitment of End Users

Figure 4: Completed Cross-Impact-Matrix for 'Anonymized City' (left) and Criticality of Impact Factors, as a Result of the Impact Assessment (right) (Source: own figure, unassigned to any concrete city)[xix]

As a result, the total criticality of the factors is manifested in its aggregated active and passive impact scores (Figure 4, to the right). Each factor was thus located in a criticality graph with the passive sum on the abscissa and the active sum on the ordinate. Factors that are particularly sensible have both high active and passive sums, highlighting particular 'critical nodes' in the system, while factors with low sums are rather slowly reacting or buffering. However, even the latter may be important in singular cases for further cascading effects. Possible second, third and fourth order cascading effects can be shown through further analytical steps of impact chain analysis.

Combination of Qualitative and Quantitative (GIS) Analysis

While the above steps helped selecting particularly sensitive or critical nodes within the entire system of systems, the performed GIS analysis was then used to a) map the selected elements and zoom into the respective interdependencies and b) identify critical nodes and interdependencies that had been overseen in the qualitative analysis. An extreme flood scenario was chosen for GIS simulation. To show the possible impacts of the flood, the following figure visualizes selected elements of different CIs (fuel stations, emergency response and electricity distribution assets) exemplarily for the city of Cologne, using OS data and non-sensitive information (Figure 5).

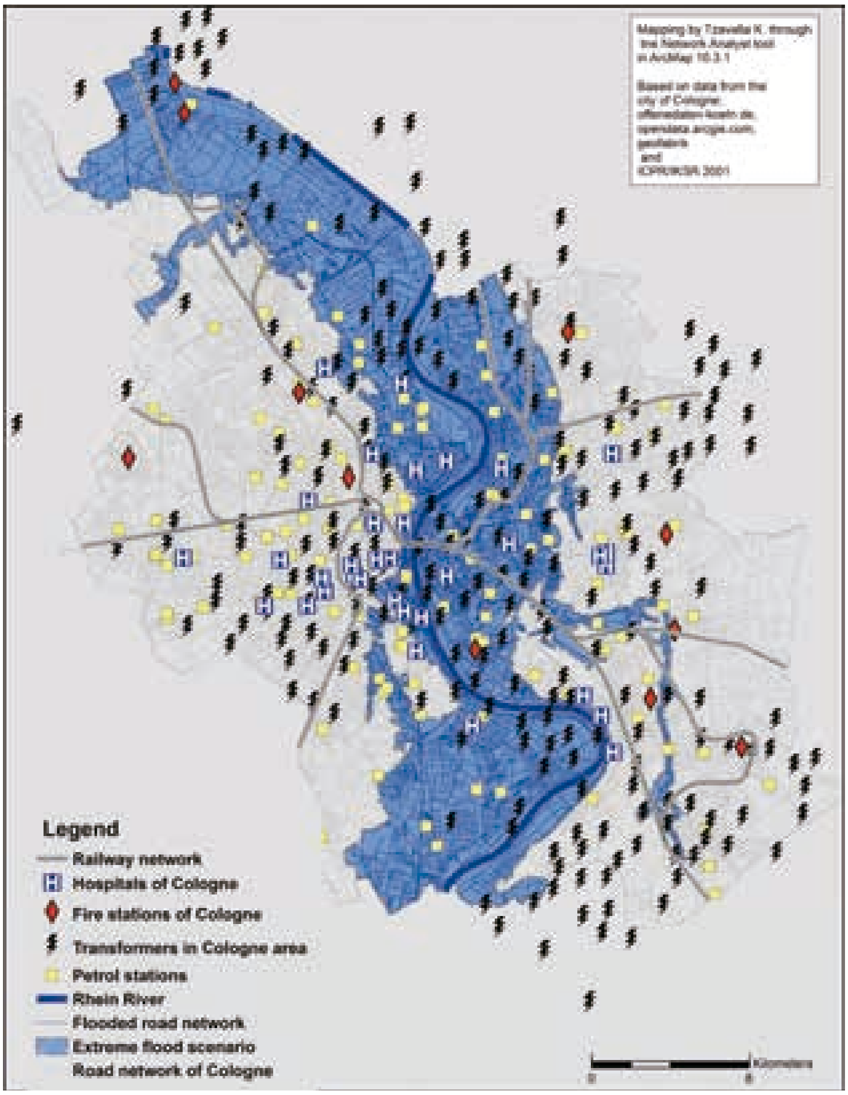


Figure 5: Different CIs of the city of Cologne affected by the extreme flood scenario (Source: own figure using open source data)

First of all, in Figure 5, the spatial exposure assessment of the different CIs to an extreme flood scenario reveals their geographical interdependency, as various CIs are exposed to flood at the same time. Furthermore, the map points to dependency of some of the above-mentioned elements (e.g. repairing activities and emergency response/firefighting) on the transportation network, fuel supply, and electricity supply. In this way, the result of the cross-impact-analysis was verified, even showing that the impact might have been underestimated given the geographical interdependency. The identification of such geographical interdependencies and their integration into an emergency response plan has been covered in detail in Tzavella et al. (2017). From the above results of the qualitative analysis steps, it was further derived that traffic is a critical impact factor and should be taken into consideration in repairing management, for operative-tactical emergency/crisis management and for flood control.

In order to test these results and get a more precise understanding of their implications for a distinct scenario, GIS data on traffic density (high road network density and high traffic lights density) was combined with the location of transformers and the flooded areas. This yielded precisely, which transformers need to be disconnected due to flooding, and thus which roads, traffic lights and intersections are most critical or – on the other hand – which ones would presumably not be as much affected as it seems from the more general qualitative analysis. Thus, effects on response and repairing time (of emergency responders and critical infrastructure repair management) can be calculated and alternative routes considered. In Figure 6, it is shown that some transformers are located in the flooded area. Emergency managers can use such information for planning repair times, considering contraints such as the driving time through flooded road networks (Fekete et al., 2016; Tzavella et al., 2017).

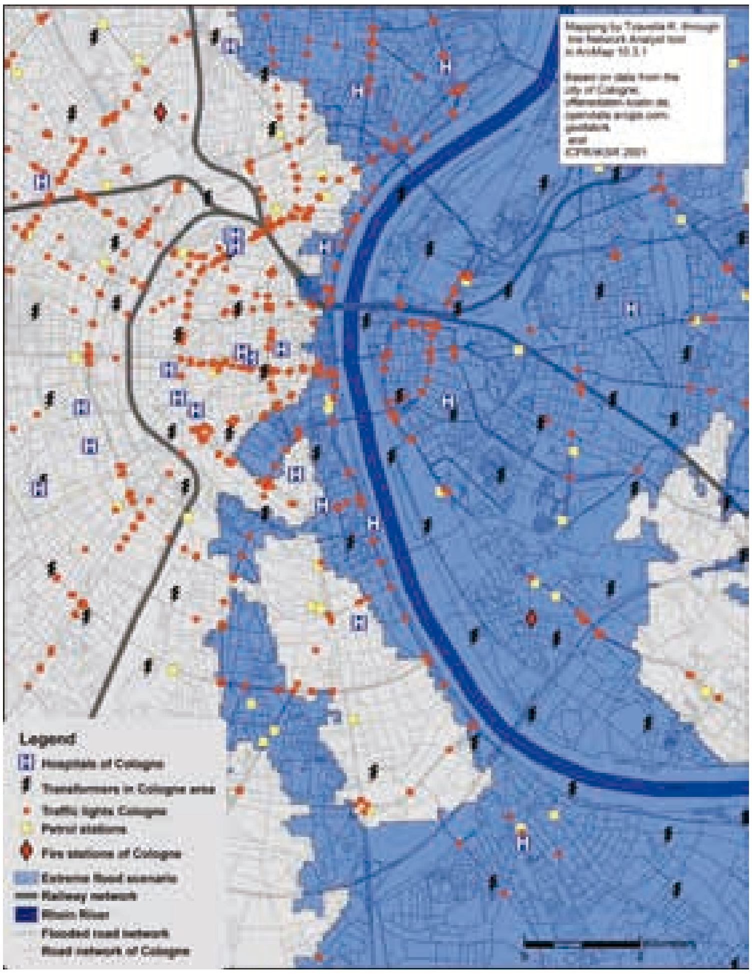


Figure 6: Critical infrastructures of Cologne affected from the flood including the traffic lights (Source: own figure using open source data)

Additionally, further **physical interdependencies** can be identified using GIS. The road and the railway networks are physically interdependent when sharing physical structure such as bridges. As observed, all the trains approaching Cologne are following railway lines that are crossing major road network segments. A bridge can also carry water lines, IT and gas lines. A failure in these areas could indicate a cascading effect of failures in the day-to-day functionality of the city.

The identification of these physical interdependencies and the information that is provided regarding the potential cascading effects mentioned above, could only be addressed through the quantitative analysis with GIS visualizations of datasets, as they had not been identified before by the stakeholders during the phase of qualitative analyses. Also, the results of GIS analysis displayed interdependencies that were implied and “hidden” in combinatory nodes between the different interdependent elements and were unidentified through the qualitative analysis. This identification of the CI at risk adds value to the situational awareness phase of the emergency management, leading to a timely effective emergency response.

Additional information yielded by the quantitative analysis can be fed back into the cross-impact-analysis, and of course the preliminary system analysis. It can thus provide supplemental and more precise information for rethinking the sensitivities between the impact factors.

DISCUSSION: POTENTIALS AND CHALLENGES OF PARTICIPATORY QUALITATIVE-QUANTITATIVE ANALYSIS

The applied approach brings about the advantage of capturing experiences and subjective opinions of the participating stakeholders and experts, allowing them to indicate the most critical aspects and challenges they face in preparing possible supply disruptions. Compared to the existing recent methods of EU research projects discussed in the literature review, this method has a similar orientation, given its interdisciplinary and participatory character, but offers a viable solution to the challenge of data acquisition and management.

Specific Methodologic Advantages and Limitations

In comparison to preceding work, the approach disposes of three major advantages: It

i) allows for assessing the interdependencies between various systems and actors at the local level and thus serves as an iterative informational/advisory system for the decision makers,

ii) does not demand precise data sets from the participants, thus avoiding the often-insurmountable obstacle of sensitive data sharing or even costly data collection (Garcia-Aristizabal et al., 2015), and yet

iii) provides relevant information both in specific detail (combined qualitative description of key elements and analysis of their nodes and quantitative GIS analysis), as well as on a more abstract but all-embracing level (cross-impact-analysis using aggregated impact factors), thus drawing the entire picture.

The approach therefore serves as an ideal basis for further processing of information, e.g. in building reliable scenarios, or building up a systematized geo-databases (see e.g. Herrera et al., 2015). In particular, it can serve for providing an appropriate informational basis for interorganizational crisis communication and joint situation analysis tools, such as AlphaKomm (Töppel et al., 2017) or its predecessor SIMKAS-3D. However, even though the system and cross-impact, as well as geospatial analyses can be performed in detail for the interconnections between different (sub-)systems, it will only be able to serve as an important informational basis for a general understanding of the functionality of systems and their embeddedness, and for local or regional crisis-scenario-analysis. Further data-based and detailed analysis is still needed when it comes to precisely understanding technical interfaces.

The Challenge of Involving Practitioners and Exchanging Information

The chosen format of interviews and workshop discussions helped to prioritize information dialectically together with the experts. For critical system nodes and (inter)dependencies, more detailed information was gathered. Contrasting or even contradicting expert opinions could be discussed right away. On the other side, much of the subjective information gained from the experts needed to be cross-checked with other expert statements and information from existing research or other reliable sources. Concerning particularly the GIS analysis, plausibility checks through the involved experts allowed for valuable outcomes even from analyses based on lower quality open source data.

Initially, the participatory procedure faced the challenge of building trust between the involved experts and the researchers. As it demanded much time from the former to provide the needed information in workshops and interviews, they showed a certain initial skepticism. This however vanished at the point when they more clearly saw the direct benefit for themselves, namely, to exchange information about mutual dependencies and weaknesses for the first time outside of specific exercises or formal frameworks. CI operators and emergency responders recognized that they have had contrasting expectations or an incomplete understanding of service availability of the other CIs in crisis situations beforehand. They turned out to be willing to providing insights into dependencies and crisis management of their companies.

During focus group discussions, the associated partners and other potential users were repeatedly shown demonstrators of the interdependency and GIS assessments and interview results. They were asked not only to give feedback on possible improvements, but also to indicate further demands and type of documentation so they could benefit from the results. The stakeholders confirmed their usefulness e.g. in terms of i) justification of their work on security and emergency management, ii) intensifying the CIRMin-triggered knowledge exchange parallel and even after the end of the project (in bilateral collaborations) and iii) applying GIS planning instruments for emergency back-ups and resource planning.

CONCLUSION AND OUTLOOK

The interdependency analysis presented here offers several advantages, namely that it provides a way to understanding how different CI systems function i) separately (identification of system structures within each sector) and ii) in interaction (intersectoral interdependencies). Based on qualitative information and analysis, it captures not only the structure, but also the dynamic between technical, social, and communicative elements of the CI systems. This is important for being able to adopt effective resilience-building (Kröger, 2012). The combination of qualitative and GIS (quantitative) interdependency analysis yielded a comprehensive overview of what measures are needed for coping with possible disruptions and maintaining the functionalities of CI in crisis situations. It points out to indispensably needed resources for CI operation, redundancies in the supply networks and auxiliary powers, and gives hints how to optimize repairing activities, crisis management and response time. Also, in the particular research context, the documented approach helped identifying critical elements and impact factors that are relevant for providing minimal (or reduced) supply for the population. Such provision can enhance the resilience of the population to specific risks, since a thorough crisis preparation allows for a quicker bounce back to normal.

As an add-on to the documented analytical work and subject to further research, cascading effects may be visualized in the form of risk maps, showing the affected elements and their risk level to fail. This would require further spatial analyses, classifications and weighting of criticality levels, as well as a categorization of processes according to geographical relations. The resulting maps would finally provide an aggregated criticality level of the different elements per area.

Even though CI systems inside and outside of cities differ in detail, their main structures, processes and interdependencies show similarities. The presented methodological approach can hence be transferred to other areas, by some limitations: Firstly, the authors are at the same time involved as observers and participants in such a participatory approach (Fekete, 2012b). This limits their abilities to recognize certain constraints. Secondly, all case studies are located within the same region. Nonetheless, if key conditions are comparable, transferability should be possible to other German regions and even into other countries. Thirdly, readiness for co-creating knowledge is the decisive factor for applying the approach presented here.

ACKNOWLEDGEMENT

CIRMin is funded by the German Ministry of Education and Research (BMBF) from 6/2016 to 5/2019 in the context of the research program "Zivile Sicherheit – Erhöhung der Resilienz im Krisen- und Katastrophenfall".

REFERENCES

Bach, C., Bouchon, S., Fekete, A., Birkmann, J. and Serre, D. (2013) Adding Value to Critical Infrastructure Research and Disaster Risk Management. The Resilience Concept, *S.A.P.I.EN.S*, 6(1), 1-12.

Bagheri, E. and Ghorbani, A.A. (2008) The state of the art in critical infrastructure protection: a framework for convergence, *International Journal of Critical Infrastructures*, 4(3), 215 - 244.

Baloye, D. and Palamuleni, L. (2016) Modelling a critical infrastructure-driven spatial database for proactive disaster management: a developing country context, *Jàmbá - Journal of Disaster Risk Studies*, 8(14), 8(1), a220. http://dx.doi.org/10.4102/jamba.v8i1.220.

Barthe-Delanoë, A.-M., Trupti, S. and Bénaben, F. (2015) Towards a taxonomy of crisis management simulation tools, In Palen, L., Büscher, M., Comes,T. and Hughes, A. (Eds.) *Proceedings of the ISCRAM 2015 Conference - Kristiansand, May 24-27*.

Bloomfield, R., Chozos, N., and Nobles, P. (2009) Infrastructure interdependency analysis: Requirements, capabilities and strategy, Adelard LLP, London, UK.

Brennan-Horley, C. and Gibson, C. (2009) Where is creativity in the city? Integrating qualitative and GIS methods, *Environment and Planning*, 41, 2595-2614.

Clarke, L. (1999) Mission improbable: Using fantasy documents to tame disaster, The University of Chicago Press, Chicago/ London.

Dierich, A., Schön, S., Bartels, M., Hahne, M., Hempel, L. and Lieb, R. (2012) Szenarioanalyse für intersektorales Infrastruktur-Management, *energie | wasser-praxis,* 6, 20-23.

Dudenhoeffer, D. and Permann, M. (2006) CIMS: A Framework for Infrastructure Interdependency Modelling and Analysis, In Perrone, L. F., Wieland, F.P, Liu, J, Lawson, B.G., Nicol D.M. and Fujimoto, R.M. (Eds.) *Proceedings of the 2006 Winter Simulation Conference. The 2006 Winter Simulation Conference, Monterey, CA, USA, 3.-6. Dez 2006,* 478–485.

Enzer, S. (1972) Cross-Impact Techniques in Technology Assessment, *Futures* March 1972, 30-51.

European Commission (2008) Council Directive 2008/114/ Ec of 8 December 2008 on the Identification and Designation of European Critical Infrastructures and the Assessment of the Need to Improve Their Protection, *Official Journal of the European Union*, 23.12.2008, L 345/75-82.

Faturechi, R, and Miller-Hooks, E. (2015) Measuring the performance of transportation infrastructure systems in disasters: a comprehensive review, *J Infrastruct Syst*, 21(1), 04014025

FMIG - Federal Ministry of the Interior of Germany (2009) National Strategy for Critical Infrastructure Protection (CIP Strategy), Berlin.

Fekete, A. (2012a) Spatial Disaster Vulnerability and Risk Assessments: Challenges in Their Quality and Acceptance, *Natural Hazards,* 61(3), 1161-78.

Fekete, A. (2012b) Safety and Security Target Levels: Opportunities and Challenges for Risk Management and Risk Communication, *International Journal of Disaster Risk Reduction,* 67-76.

Fekete, A., Tzavella, K. and Baumhauer, R. (2016) Spatial exposure aspects contributing to vulnerability and resilience assessments of urban critical infrastructure in a flood and blackout context, *Natural Hazards,* 1-26.

Fekete, A., Tzavella, K. and Baumhauer, R. (2017) Spatial Exposure Aspects Contributing to Vulnerability and Resilience Assessments of Urban Critical Infrastructure in a Flood and Blackout Context, *Natural Hazards,* 86(1), 151-76.

GAR (2015) Global assessment report on disaster risk reduction, UNISDR.

Garcia-Aristizabal, A., Zuccaro, G., Aubrecht, C., Polese, M. and Almeida, M. (2015) Improving emergency preparedness with simulation of cascading events scenarios, In Palen, L., Büscher P.; M., Comes, T. and Hughes, A. (Eds.) *Proceedings of the ISCRAM 2015 Conference - Kristiansand, May 24-27*.

Gordon, T., & H. Hayward (1968): Initial Experiments with the Cross Impact Matrix Method of Forecasting. In: *Futures 1(2),* pp. 100–116.

Grafenauer, T., König, S., Rass, S. and S. Schauer (2018) A simulation tool for cascading effects in interdependent critical infrastructures. In Proceedings of the 13th International Conference on Availability, Reliability and Security (ARES 2018). ACM, New York, NY, USA,

Giannopoulos, G., Filippini, R. and Schimmer, M. (2012) Risk assessment methodologies for Critical Infrastructure Protection. Part I: A state of the art*, Joint Research Centre – Institute for the Protection and Security of the Citizen. Luxembourg,* Publications Office of the European Union, Luxembourg.

Heinecke, A. (2006) Die Anwendung induktiver Verfahren in der Szenario-Technik. In Wilms, F.E.P. (Ed.) Szenariotechnik. Vom Umgang mit der Zukunft, Haupt, Berne, Switzerland, 183-213.

Helmer, O. (1983) Looking Forward. A Guide to Futures Research, Sage Publications, Beverly Hills, CA, USA.

Herrera, M., Batista e Silva, F., Bianchi, A., Barranco, R. and Lavalle, C. (2015) A geographical database of Infrastructures in Europe. A contribution to the knowledge base of the LUISA modelling platform. *Joint Research Center, European Union*, Brussels.

Hokstad, P., Utne, I. B., and Vatn, J. (2012) Interdependency Modelling in Risk Analysis. In Hokstad, P., Utne, I. B., and Vatn, J. (Eds.) *Risk and Interdependencies in Critical Infrastructures. A Guideline for Analysis,* Springer, London, 2012, 35-48.

inter 3 - Institut für Ressourcenmanagement (2013) *Simkas 3D:* Simulation von intersektoriellen Kaskadeneffekten bei Ausfällen von Versorgungsinfrastrukturen unter Verwendung des virtuellen 3D-Stadtmodells von Berlin, Teilvorhaben: Untersuchung sektoriell übergreifender Szenarien; Abschlussbericht, Technische Informationsbibliothek Hannover, Hannover.

Kosow, H. & Gaßner, R. (2008) Methoden der Zukunfts- und Szenarioanalyse. Überblick, Bewertung und Auswahlkriterien. WerkstattBericht Nr. 103, IZT – Institut für Zukunftsstudien und Technologiebewertung Berlin. https://www.izt.de/fileadmin/downloads/pdf/IZT_WB103.pdf.

Kröger, W. (2012) Understanding Complexity and Interdependency: A prerequisite to increase resilience, In G. Giannopoulos, G. and Filippini, R. (Eds.) *Risk Assessment and Resilience for Critical Infrastructures. Workshop Proceedings 25-26 April 2012, Ranco, Italy*, 41-52.

Kwan, M. and Knigge, L. (2006) Doing qualitative research using GIS: An oxymoronic endeavor*?*, *Environment and Planning A*, 38, 1999-2002. 10.1068/a38462.

Lenz, S. (2009) Vulnerabilität Kritischer Infrastrukturen, In Bundesamt für Bevölkerungsschutz und Katastrophenhilfe (Eds.) *Forschung im Bevölkerungsschutz, Band 4*, Bonn.

Little, R.G. (2002) Controlling Cascading Failure: Understanding the Vulnerabilities of Interconnected Infrastructures, *Journal of Urban Technology*, 9(1), 109–123.

López-Silva, J., Bañuls, V.A. and Turoff, M. (2015) Scenario Based Approach for Risks Analysis in Critical Infrastructures. In Palen, L., Büscher P.; M., Comes, T. and Hughes, A. (Eds.) *Proceedings of the ISCRAM 2015 Conference*, Kristiansand.

Malik Management Zentrum St. Gallen (2014) Malik Sensitivity Model®Prof. Vester: The Computerized System Tools for a New Management of Complex Problems, St. Gallen.

Mansor, S., Mohammed, A.S., Lawal, B., Iwan, S. and Faisal, J. (2004) Spatial technology for natural risk management, *Disaster Prev Manag*, 13(5), 364–373.

O´Rourke, T. D. (2007) Critical Infrastructure, Interdependencies, and Resilience, *The Bridge - Linking Engineering and Society*, 37(1), 22–29.

Ouyang, M. (2014) Review on modeling and simulation of interdependent critical infrastructure systems, *Reliability Engineering & System Safety*, 121, 43–60. DOI: 10.1016/j.ress.2013.06.040.

Pederson, P., Dudenhoeffer, D., Hartley, S. and Permann, M. (2006) Critical Infrastructure Interdependency Modelling: A Survey of U.S. and International Research, Idaho National Laboratory, Idaho Falls, Idaho.

Perrow, C. (1984). *Normal accidents*, Basic Books, New York, NY.

Petermann, T., Bradke, H., Lüllmann, A., Poetzsch, M. and Riehm, U. (2010) Gefährdung und Verletzbarkeit moderner Gesellschaften – am Beispiel eines großräumigen Ausfalls der Stromversorgung (Endbericht zum TA-Projekt. Arbeitsbericht Nr. 141), Büro für Technikfolgen-Abschätzung beim Deutschen Bundestag, Berlin.

Petit, F., Wallace, K. und Phillips, J. (2014) An Approach to Critical Infrastructure Resilience, *The CIP Report, Center for Infrastructure Protection and Homeland Security*, George Mason University School of Law Washington D.C., 12(7), 17–20.

Petit, F., Verner, D., Brannegan, D., Buehring, W., Dickinson D., Guziel, K., Haffenden, R., Philips, J. and Peerenboorn, J. (2015) Analysis of Critical Infrastructure Dependencies and Interdependencies. Argonne National Laboratory, Technical Report N° ANL/GSS-15/4111906, Argonne, US.

Pfeffer, K.., Martinez, J., Baud, I. and Sridharan, N. (2011) Knowledge Production in Urban Governance Systems through Qualitative Geographical Information Systems (GIS), *Environment and Urbanization ASIA*, 2(2), 235-250.

Reissberg, A. C. (2012) Managing natural catastrophies: Viable Systems to prevent human tragedy - the Hawai'ian example, Campus Verlag, Frankfurt a.M., Germany.

Rinaldi, S. M., Peerenboom, J. P. and Kelly, T. K. (2001) Identifying, Understanding, and Analyzing Critical Infrastructure Interdependencies, *IEEE Control Systems Magazine*, December 2001, 1–25.

Robert B, Morabito, L., Cloutier, I. and Hémond, Y. (2015) Interdependent critical infrastructures resilience: Methodology and case study, *Disaster Prevention and Management*, 24(1), 70-79.

Schätter, F., Wiens, M., Meng, S. and Schultmann, F. (2014) A multi - stage scenario construction approach for critical infrastructure protection, In Hiltz, S.R., Pfaff ,M.S., Plotnick, L, and Shih, P.C (Eds.) *Proceedings of the 11th International ISCRAM Conference, Pennsylvania, USA, May 18-21, 2014*, 399–408.

Töppel, M., Hahne, M. and Bartels, M. (2017) Informationsvorlagen für die interorganisationale Kommunikation im Krisenfall, *Crisis Prevention*, 1/2017. https://crisis-prevention.de/feuerwehr-katastrophenschutz/informationsvorlagen-fuer-die-interorganisationale-kommunikation-im-krisenfall

Turoff, M.; Bañuls, V.A.; Plotnick, L.; Hiltz, S.R. (2014) Development of a Dynamic Scenario Model for the Interaction of Critical Infrastructures, In Hiltz, S.R., Pfaff ,M.S., Plotnick, L, and Shih, P.C (Eds.) *Proceedings of the 11th International ISCRAM Conference, Pennsylvania, USA, May 18-21, 2014*, 414-423.

Tzavella, K., Fekete, A. and Fiedrich, F. (2017) Opportunities provided by geographic information systems and volunteered geographic information for a timely emergency response during flood events in Cologne, Germany, *Natural Hazards* (2018) 91(Suppl 1): 29. https://doi.org/10.1007/s11069-017-3102-1

US Government (1996) The President's Commission on Critical Infrastructure Protection (Pccip), Executive Order 13010, Washington, DC.

Utne, I. B., Hokstad, P. and Vatn, J. (2011). A method for risk modeling of interdependencies in critical infrastructures, *Reliability Engineering & System Safety*, 96 (6), 671–678. DOI: 10.1016/j.ress.2010.12.006.

Vester, F. (2012) Die Kunst vernetzt zu denken. Ideen und Werkzeuge für einen neuen Umgang mit Komplexität. Ein Bericht an den Club of Rome, 9. aktualisierte Ausgabe, DTB, Munich, Germany.

Vester, F. (1991) Ausfahrt Zukunft Supplement. Material zur Systemuntersuchung, Studiengruppe für Biologie und Umwelt GmbH, Munich, Germany.

Vester, F. (1988). The Biocybernetic Approach as a Basis for Planning Our Environment, *Systems Practice*, 1(4), 399-413.

Weimer-Jehle W. (2015) Cross-Impact-Analyse. In: Niederberger M., Wassermann S. (Eds) Methoden der Experten- und Stakeholdereinbindung in der sozialwissenschaftlichen Forschung. Springer VS, Wiesbaden, 243-258.

Wilms, F.E.P. (2006) Szenarien sind Systeme. In ibid (Ed.) Szenariotechnik. Vom Umgang mit der Zukunft, Haupt, Berne, Switzerland, 39-59.

[i] https://cordis.europa.eu/project/rcn/88359_en.html
[ii] http://www.after-project.eu/Layout/after/
[iii] http://www.tanknotstrom.de/
[iv] https://www.bbk.bund.de/DE/Service/Fachinformationsstelle/Informationsangebote/Forschungsberichte/ForschungKritischeInfrastrukturen/Energie/MIA/MIA_node.html
[v] http://www.strest-eu.org/
[vi] http://www.smartresilience.eu-vri.eu/
[vii] https://www.unibw.de/wasserwesen/swa/nowa
[viii] https://www.kontikat.de/
[ix] http://casceff.eu/publications/
[x] http://www.predict-project.eu/about-0
[xi] http://www.driver-project.eu/
[xii] http://www.crismaproject.eu/
[xiii] http://snowball-project.eu/outputs/
[xiv] https://cordis.europa.eu/result/rcn/182552_en.html
[xv] https://pro.arcgis.com/en/pro-app/help/data/data-interoperability/spatial-etl-tools.htm
[xvi] https://www.geofabrik.de/en/
[xvii] http://www.offenedaten-koeln.de/
[xviii] http://www.iksr.org/
[xix] In this modified and unassigned example cross-impact-matrix, (external) electricity generation and supply has been omitted, as it is not under control of the anonymous city.