An Integrated Multi-Criteria Approach on Vulnerability Analysis in the Context of Load Reduction

Thomas Münzberg
Karlsruhe Institute of Technology,
Institute for Nuclear and Energy Technologies
thomas.muenzberg@kit.edu

Tim Müller
Karlsruhe Institute of Technology,
Institute for Nuclear and Energy Technologies
tim.mueller@kit.edu

Stella Möhrle
Karlsruhe Institute of Technology,
Institute for Nuclear and Energy Technologies
Stella.moehrle@kit.edu

Tina Comes
Karlsruhe Institute of Technology,
Institute for Industrial Production
comes@kit.edu

Frank Schultmann
Karlsruhe Institute of Technology,
Institute for Industrial Production
frank.schultmann@kit.edu

ABSTRACT

Load reduction is an emergency measure to stabilize an electrical grid by decoupling some supply areas to balance the demand and supply of electricity in power grids. In the decoupled areas, power outages may cause important consequences, which may propagate further via the network of interdependent infrastructures. Therefore, support is needed to choose the regions to be decoupled. This paper describes an approach to analyze the risk triggered by load reduction that can be used for disaster management and load reduction scheme optimization. The core of our work is the vulnerability assessment that takes into account the consequences of load reduction on economy and society. The approach facilitates participatory decision support by making the vulnerability of regions especially in urban transparent.

Keywords

Multi-Criteria Decision Analysis, Load Reduction, Vulnerability Assessment, Critical Infrastructure Disruption, Disaster risk management

INTRODUCTION

The electricity grid is one of the most important Critical Infrastructures (CIs). As the grid is highly interdependent on all other CIs on electricity (Rinaldi, 2004), power outages can cause important direct and indirect economic losses (Merz, 2011). Recently in autumn 2012, hurricane 'Sandy' revealed the serious social impacts and effects of long-lasting and wide-area power outages on CIs (CEDIM, 2012).

Power systems are not only threatened by extreme events like hurricanes, floods, and earthquakes, they are increasingly stressed by the need to integrate new utilities and the ongoing transformation towards more renewables and a low-carbon system. As a result, power systems are operated closer to their stability limits, today (Haidar, Mohamed and Hussain, 2010). Measures to ensure service stability are more and more important. Preparing these measures is a daily business for the power system providers. One of these emergency measures is 'load reduction' (LR), the deliberate decoupling of parts of the power system to stabilize the grid. LR can prevent the total collapse of a grid and a large-area blackout after an unforeseen (catastrophic) event, thus making grids more resilient against negative impacts. Usually, the decoupling is limited to few hours. Particularly the decision which grid parts should be decoupled is difficult, as multiple issues (consequences of LR on economy, industry and society) and the (conflicting) interests of a high number of stakeholders need to be taken into account. In Germany, however, grid operators choose parts of the power system to be decoupled in a non-discriminatory manner. In other countries LR is often realized with little to no discrimination between costumer, too (e.g. Australia, Ireland). German grid operators do not take into account the socio-economic consequences of power outages. The approach presented in this paper addresses this issue by considering the regional vulnerabilities in a city or municipality.

Although LR is an effective emergency measure, it increases the risk of power blackouts in LR affected regions, with potentially severe consequences for the population, further CIs, industry and economy in the affected grid part. Through CI interdependencies and cascades, regions of other grid parts can be affected, too. An integrated and holistic approach is required to make the consequences transparent and facilitate the decision making process by taking vulnerabilities into account, which are the basis for efficient risk management (Merz, Hiete, Comes and Schultmann, 2012). As the concept of vulnerability is vague and often abstract (Birkmann, 2006), the main objectives of this paper are (i) the development of a clear and well-structured framework to assess socio-economic vulnerabilities against power outages and (ii) to rank the vulnerabilities of SR to support LR planning.

The paper is organized as follows. First, an overview of LR schemes is presented. Second, the management of power outages in Germany is discussed. Third, the multi-fold consequences caused by LR-induced power outages are introduced. Thereafter, the approach for an integrated approach is presented. In order to assess socio-economic vulnerability, a multi-criteria framework is introduced. The approach is substantiated by a use case as referred to in the following section. Finally, the results and future work are discussed followed by a conclusion.

RESEARCH ON LOAD REDUCTION SCHEMES

Although LR is one of the most effective emergency measures to stabilize the power grid (Dong, Lou and Wong, 2008), as it has a direct impact on the population, economy, and industry, it is usually among the very last measures to be implemented and typically only used to avoid the total collapse of a grid. Two types of grids are distinguished, transportation and distribution grids. This study refers to LR in distribution grids. In this context, the grid areas to be decoupled are referred to SRs. SRs are determined individually by the grid topology and normally predefined as the areas supplied by single distribution transformer feeders. Transformer feeders are important grid components that distribute electricity to the costumers. The number of transformer feeders depends on the distribution grid network topology. Each transformer feeder supplies one discrete region with electricity in a distribution grid. A region supplied by one transformer feeder is the SR. A distribution grid consists of a number of transformer feeders and, hence, of the same number of SRs. If LR is necessary, some distribution transformer feeders are decoupled from the grid, thus causing a power outage in these SRs. Today, German grid operators choose the SRs to be decoupled from a grid in a highly non-discriminatory way. This means SR are selected by chance without taking the consequences of power outages into account. Additionally, a blackout in a selected SR will only last a couple of hours. If LR is still necessary after a first LR period, other SR will be selected to be decoupled in the same non-discriminatory way.

LR prevents a complete system collapse by minimizing the technical weaknesses of the grid and making it more robust to unforeseen negative impacts. LR has been implemented successfully in Europe and the U.S.. Most recently, LR was applied successfully in the management of the impacts of the 2012 hurricane Sandy, in ‘The 2006 European Blackout’ (van der Vleuten and Lagendijk, 2010), in ‘The Northeast Blackout 2003’ (Andersson and Donalek, 2005), and in ‘The Italian 2003 Blackout’ (Berizzi, 2004).

In the last decade, research into LR planning concentrated on optimizing the scheme planning. While technical systems were enhanced, an integrated approach to including an assessment of the individual SR’s vulnerabilities to power outages is still lacking (Delfino, Massucco, Morini, Scalera and Silvestro, 2001; Dong et al., 2008; Girgis and Mathure, 2012; Haidar, Mohamed, and Hussain 2010; Haidar, Mohamed, and Milano 2010; Mostafa and El-Hawary 1996; Song and Kezunovic 2007;Dong, Lou and Wong, 2008, Rudez and Mihalic 2011). The assessment of an SR’s vulnerabilities is a new and essential problem in load reduction planning and disaster risk management and called ‘the SR vulnerability problem’.

COPING WITH POWER OUTAGES IN DISASTER RISK MANAGEMENT

To ensure an end user oriented development of decision support approach, it is important to analyze current disaster management for coping with the consequences of power outages. As terms, regulations, norms, standards and legislations vary greatly between countries, our approach is based on Germany as an example. This ensures the practical relevance and allows us to test the model with (potential) users.

According to German laws on disaster control and civil protection, disastrous far-reaching and long-term CI disruptions like power blackouts are usually classified as ‘major disaster incidents’. In the German disaster management system, the Local Emergency Management Agencies (LEMAs) are primarily responsible for the management of such major disaster incidents, too (German Federal Ministry of the Interior, 2010). Each LEMA is responsible for a municipality. The LEMAs' task is to minimize negative impacts on society and economy. This includes managing the risk of CI disruptions as well as the impacts when CI disruption could not be avoided.

In Germany most CIs are operated by private companies (German Federal Ministry of the Interior, 2010). Therefore, LEMAs, CI providers and stakeholders need to cooperate to prepare for and manage CI disruptions. Additionally, resources are typically scarce and LEMAs can hardly request further response resources from other authorities. Although the impact of power blackouts may not be limited to one municipality (particularly indirect impacts), neither the federal states nor the German federation are in charge for the management of major disaster incidents. Local collaboration of different actors and stakeholders is a key to better disaster risk management for CI disruptions cases. Different approaches have been developed to improve knowledge management (e.g. Gronau, Röchert-Voigt and Proske, 2011), collaborative decision making (e.g. Raskob, Tufte, Gers, Meyer-zu-Drewer, Möllmann and Stärk, 2011), Simulation and Modeling (Hernantes, Labaka, Laugé and Sarriegi, 2012), and inter-organizational management (e.g. Wiedenhöfer, Reuter, Ley and Pipek, 2009). Additionally, protection targets are discussed (Fekete, Lauwe and Geier 2012) and vulnerability research (Birkmann, 2006) is conducted to facilitate decision making for CI protection.

The understanding of an area's vulnerability allows to assess the socio-economic impact of a power blackout *before* it actually happens. It is the basis for mitigating the consequences. As decisions need to be made by the LEMAs and CI providers, this paper divides municipalities into a set of SRs that are determined by the topology of the grid. SRs contain different types and numbers of CIs. Hence, the consequences to be expected when power outages occur in these SRs differ as well. Figure 1 displays a hypothetical example.

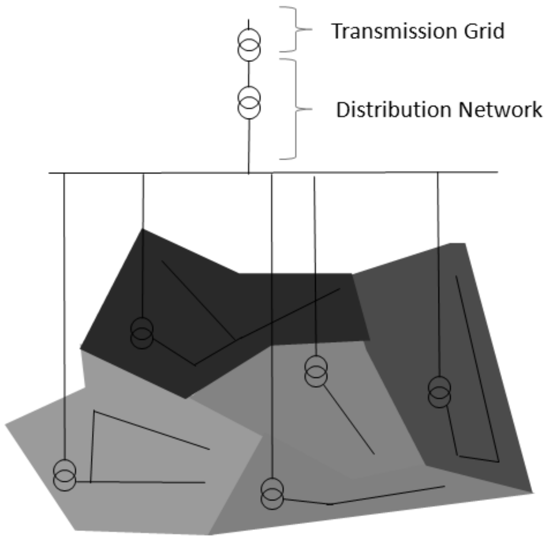

Figure 1. A simplified example of supply regions in a municipality.

The approach described in this paper is designed to support decision-making processes of collaborative partnerships on the local level. Comparisons of SRs should be made understandable and transparent so as to facilitate disaster risk management by taking the consequences of power outages into account.

THE RISK OF LOAD REDUCTION CAUSING POWER OUTAGES

Power outages put the affected region at risk. In disaster risk management, "risk" (R) is defined as a loss with a given probability. Often, the risk of an event *n* is defined as a product of hazard (H), vulnerability (V) and exposure (E) to n (Merz et al. 2012): $R_n = H_n \cdot E_n \cdot V_n = R = H \times E \times V$. This section will first outlines briefly how this approach is typically understood and implemented, before adapting it to the problem of LR planning and disaster risk management.

Usually, the exposure E is understood to be the value of assets at risk, i.e. , they are 'exposed' to hazard H , which is described by its severity and probability (Hiete and Merz, 2009). Vulnerability is a somewhat abstract concept, for which a unique standard definition has not (yet) been defined (Aven, 2007; Cardona, 2004). For our purposes, we define vulnerability V to ne the condition of physical, social, and economic factors, increasing the susceptibility of an SR's community to power outages.

For the problems in this paper the hazard H can be described by the severity of power outages in a specific region and the probability of blackout *assuming* that a specific SR was selected for LR. Similarly, also the exposure depends on the SRs selected. Consequently, the risk for LR-caused power outages can be defined by

$$R_{(\text{power outage in municipality j})} = H_{(\text{poweroutage in municipality j | SR})} \cdot E_{(\text{power outage in municipality j | SR})} \cdot V_{(SR)} .$$

For a more precise definition of vulnerability, we will develop a criteria framework in the next section, which takes the CI facilities and socio-economic impacts of power outages into account and will help understand the SR's vulnerabilities.

MULTI-CRITERIA DECISION ANALYSIS IN VULNERABILITY ASSESSMENT

Multi-criteria decision analysis (MCDA) is an umbrella term for various methods supporting decision making taking into account multiple goals (decision criteria) in a transparent manner. We chose MCDA since it facilitates participatory decision making by integrating stakeholders' preferences. The decision problem is structured hierarchically comprising an overall goal, multiple criteria, attributes and decision alternatives (Figure 2).

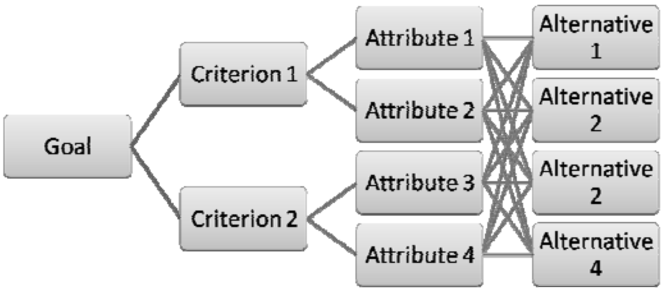

Figure 2. Hierarchical arrangement of goal, criteria, attributes and alternatives in MCDA.

The measured values of the attributes for the alternatives have to be normalized in order to make the data comparable. The choice of normalization functions is dependent on the application domain and should be considered, carefully. We propose a linear normalization function taking the minimum and maximum of the attribute values into consideration. The criteria and attributes have weight factors. Due to the hierarchical structure it holds that in each level the sum of weights of the direct successors of each node add to 1. Moreover an attribute weight is the product of weights along the path from the overall goal to each attribute. In order to calculate the overall assessment of the alternatives the weighted sum is proposed as a suitable approach. For further details concerning MCDA, see Belton and Stewart (2002), Bertsch (2008) and Triantaphyllou (2000).

Several approaches to combing vulnerability assessment and MCDA methods have been developed (Chang and Chao, 2012; Hiete and Merz, 2009; Merz et al., 2012; Özyurt, Ergin and Baykal, 2011). The approach presented in this paper opens up a new application domain since SRs are considered and their vulnerabilities are assessed by means of a specific framework and MCDA.

INTEGRATED APPROACH

The general procedure of assessing vulnerability of SRs based on an MCDA (cf. Figure 2) can be described as follows:

1. Analytical selection of criteria and attributes to assess the vulnerability of the SRs to power outages
2. Definition of a hierarchical criteria framework
3. Definition of the normalization functions
4. Integration of the weighting factors
5. Aggregation to prioritize SRs
6. Visualization of results
7. Sensitivity analysis concerning changing weights and attribute values accompanied by an update of the criteria framework
8. Decision support by means of the analysis

The criteria framework proposed may be used for the discussions and decisions of the collaborative partnerships of LEMA, CI providers and other stakeholders on the local level. It is only necessary to

1. Align the hierarchical criteria framework to the local circumstances
2. Collect data by using the established collaborative partnerships of LEMAs, CI providers and other stakeholders on the local level
3. Weight the criteria and attributes in a collaborative way
4. Perform the sensitivity analysis

This paper focuses on the analysis of the application area in general, the development of an integrated approach as a whole, and on the criteria framework to assess the vulnerabilities of SRs.

DEVELOPMENT OF A CRITERIA FRAMEWORK TO ASSESS SOCIAL-ECONOMIC VULNERABILITY

The supply regions depict the alternatives. A supply region can be decoupled from the grid or not. The potential consequences are depending from the SR's vulnerabilities. For an analytical assessment of an SR's vulnerabilities, criteria and attributes have to be selected. Birkmann (2006) discussed different kinds of theoretical frameworks for measuring vulnerabilities. For measuring of vulnerabilities of SRs, certain adjustments have to be made. To facilitate collaborative decision support, it is important to use a criteria framework that takes all exposed CI facilities in an SR into account and includes socio-economic criteria to measure potential impacts of power outages. For this purpose, criteria were distinguished for vulnerabilities of CIs as well as for socio-economic vulnerabilities. These criteria are defined in a hierarchical framework in a clear and transparent manner.

Criteria for the CIs were selected by using the definitions of CI sectors and branches based on the German CI protection strategy (German Federal Ministry of the Interior, 2010). Whereas this strategy is addressing federal interests, the definitions of branches were based on criteria reflecting a local level perspective. Taking the German CI protection strategy into account, several criteria for CI branches were selected for each CI sector criterion. To measure the socio-economic impact, the criteria 'population', 'economic impact of power outages' and 'electrical demand' were selected (see Figure 3).

Most of the attribute values present numbers of a certain objects such as hospital beds or intensive care beds. Therefore, measuring these attributes and gathering information for each of them would be more or less easy. However, taking the measurement of economic impact after power outage is challenging. There are sophisticated methods addressing this issue taking into account types of affected structures such as ratio of residential zones (Corwin and Miles, 1978). Praktiknjo, Hähnel and Erdmann (2011) apply macroeconomic approaches extended by Monte Carlo simulation to determine outage costs for electricity consumers in private households in Germany. The model can and is also applied to commercial, industrial and governmental consumers presenting a good starting point for further research.

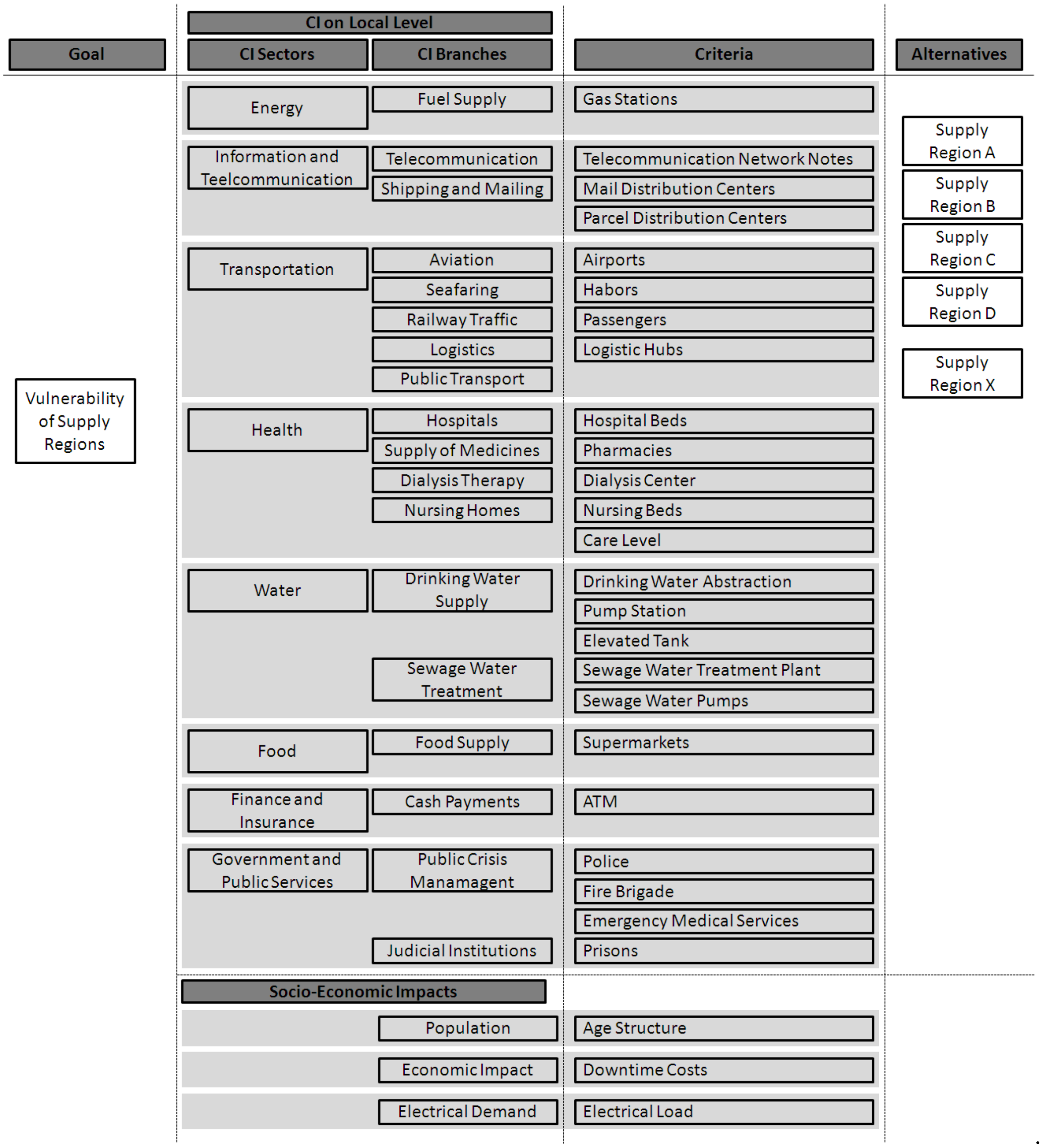

Figure 3. Hierarchical criteria framework for vulnerability assessment of SRs. The attributes are not displayed for the sake of readability.

To avoid labor-intensive work for users and to ensure end-user application availability, the criteria framework is developed to be as simple as possible. Both the CI criteria as well as the socio-economic impact criteria have to be operationalized by appropriate attributes.

Figure 4 shows an example of criteria and attributes for the CI branch ‘Hospitals’ in the CI sector ‘Health’. For these attributes values/data have to be collected.

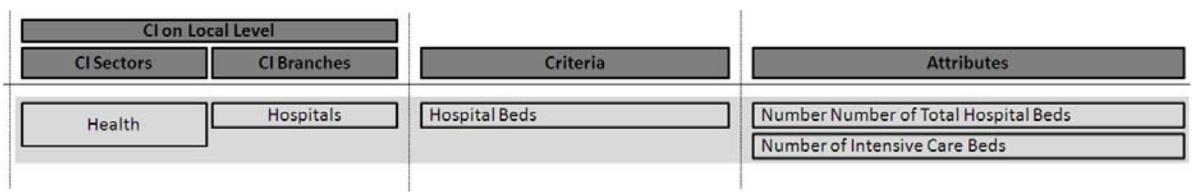

Figure 4. Example of a criterion and its detailed attributes.

In former approaches major problems relating to privacy and unavailability of data were reported. To solve these problems, Hiete and Merz (2009) used statistical data, data from literature, and data from expert opinions. The selection of attributes is based on available discrete end user data that can be quantified easily by CIP partnerships. The main attributes to be quantified are not public accessible. This data can only be gathered in an interactive way of all involved parties. The established CIP partnerships are suitable environment to gather these individual-owned stakeholder data. Additionally, on demand and in a collaborative way single criteria and attributes can be changed, deleted, and added to adjust the approach to individual purposes.

The values can be collected in a data sheet including values for each selected attribute and for all SRs. Through some information like the CI localizations may be found simpler for instance using geo information systems, the main data is owned by the individual stakeholders and not central documented. The usage of individual stakeholder data makes the theoretical framework labor intensive but improves accuracy, reliability and accessibility. Additionally, it minimizes further uncertainties and meets end-user requirements regarding confidence, completeness and precision of the results.

Use Case

The city of Mannheim in the southwest of Germany and its local distribution network provider handle the problem of load reduction in the way described above. However, they are interested in a more transparent approach that also takes into account the vulnerability of the SRs. We therefore offered to develop and apply the approach to their specific case. They supplied us with the basic data and structures of the 15 SRs of the municipality. The data were used to initially define attributes and criteria of the presented framework. Additionally meaningful attributes and criteria were identified and added to complete the framework. As the original data do not cover the complete set of attributes and criteria the affected parts of the framework were discarded in the current analysis.

The framework and data were then transferred to the MCDA tool developed by Karlsruhe Institute of Technology (KIT). In a second step the “problem of load reduction in connection with vulnerability” was discussed in a group and the weights of the criteria were interactively adapted just as an expert group (which was not available) would do. The weights are visualized as a row of bars to better evaluate them against each other and to find suitable weights in a collaborative environment. The aggregation of the attributes led to a ranking of the alternatives visualized by a stacked-bar chart for instance (see Figure 5). The chart gives an easy-to-understand impression of the general vulnerability of the SR and the contributions of the criteria and attributes to the overall assessments. The results were presented to the distributed local partnership group of LEMA, CI provider and stakeholders. So far, the response has been quite positive. In a first feedback the partners pointed out that the results had provided them with new insights in vulnerability aspects of SRs and that the transparency of the problem had been increased.

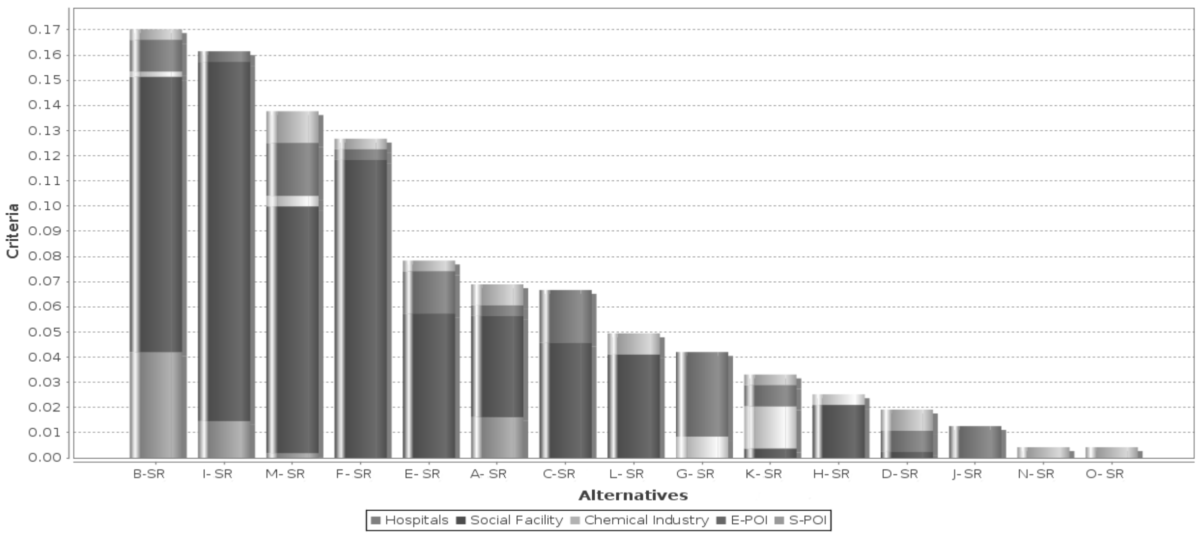

Figure 5.Visualization of the outcome by applying the framework to real life data of a local distribution network provider. The bars represent the vulnerability of a supply region ranked from highest to lowest. In this example, the

aggregated criteria of 'Hospitals', 'Social Facility', 'Chemical Industry', 'Economy Point of Interest' and 'Security Point of Interest' were used. The contribution of each of the criteria to the overall vulnerability is displayed, thus helping understanding the composition of the result and showing where to concentrate preferably.

FUTURE WORK AND DISCUSSION

The focus of this paper was on the vulnerability analysis of the SRs. The choice of appropriate SRs to be decoupled for load reduction was formulated as an optimization problem. It was aimed at selecting the SRs with the lowest vulnerability in order to achieve the required strain relief in the grid. The approach proposed has to be discussed critically as it does not yet address all issues. First, the SRs are defined by the network topology. As a result of varying topologies, different municipalities cannot be compared to each other. Compatibility with legal regulations is another important issue. The approach proposed is not non-discriminatory. This leads to legal difficulties as decoupling of an SR from the grid must be justified well. The proportionality with regard to the effort is a critical issue which has to be reflected adequately. A major future challenge is the transformation of grids. It will give rise to new options and new vulnerabilities.

A sensitivity analysis may be used to discuss the stability of the vulnerability analysis approach proposed. In particular, the effects of changes in the criteria and attribute weights and the effects of changes in the attribute values are of interest. It is necessary to determine the smallest change in criteria/attributes weights and attribute values, which leads to a change in the ranking of the alternatives. The weighting factors have to be reflected critically and impacts of small changes in the attribute values on the vulnerability of the SRs have to be identified. For further details concerning the sensitivity analysis see French (2003) and Triantaphyllou (2000).

The design of our approach has been continuously discussed with and reviewed by experts. In interviews we evaluated, the results are plausible and promising for practical applications to the expert's opinion. Still, some future researches can be made, such as the consideration of the dynamic propagation of consequence through the CI network, the resilience of CIs and regions as well as an analysis of the uncertainties present. Particularly the cascading effects have an important influence on the outcome of longer-term blackouts. While the aim of LR is actually limiting the consequences of power blackouts to the affected SRs, this may be difficult if cascading effects are important. Research on power outages has shown that the time line is very important to model buffering capacities of further regions and CIs (Hiete et al., 2010). In our future work, we will consider three approaches to improve the modeling of dynamic effects: (i) scenarios, (ii) establishing functional relations and (iii) using time-dependent attributes. First, it is possible to create different scenarios that represent a multitude of possible developments of the situation. Yet, this approach leads to a limited amount of time-series at discrete points in time only. A more sophisticated approach is to enhance the current static values of the attributes to multi-dimensional functions depending on time for instance. The third approach, which considers time-dependent attribute weights is simpler than the second. It enables CIP partners to define the weight of the attributes depending on the blackout duration, and can – if used in participatory settings – facilitate the collaborative aspect of decision making. The dynamic aspects of the analysis can be presented as multidimensional surface plots or as an animation over time e.g. as shifting value charts. It would be easy to easily to establish targets of protection for instance "the vulnerability of any SR should not fall below X within Y hours after the incident" which equals a simple threshold analysis. The MCDA software used for the analysis is not yet capable of performing this task. This is planned for the near future.

CONCLUSION

When grid instabilities occur, Load Reduction (LR) can be an effective emergency measure to stabilize grids by decoupling some SRs from the grid. To make a well-informed decision about which SRs to decouple, the potential economic, social and physical impacts of LR-induced power outages have to be taken into account. Therefore, the assessment of Supply Region (SR) vulnerabilities is essential for emergency management and the collaborative preparedness against power outages.

Here, a vulnerability triggered load reduction decision support tool is presented. Vulnerability is assessed using an integrated multi-criteria approach. The results show that the approach proposed is an effective way that enhances understanding the consequences of power outages at municipality level. When Local Emergency Management Authorities (LEMA), Critical Infrastructure (CI) providers and stakeholders involved weigh the criteria collaboratively, the tool supports inter-organizational partnerships for CI protection. Additionally, the results may be used as a basis for drafting vulnerability-triggered load reduction plans in disaster risk management, which take into account economic, social, and physical impacts.

The validity of this concept and the added value of an intelligent approach to load reduction were demonstrated by the successful application of the approach to a real life problem. Compared to the current approach of using predefined lists to switch off supply regions depending on date and time, the vulnerabilities-based approach suggested here seems to be very promising. Integration of dynamic aspects will considerably improve the innovative results displayed in this paper. Future work will address this as well as sensitivity analyses issues.

ACKNOWLEDGMENTS

The results presented were obtained under a cooperation project between the Institute for Industrial Production (IIP) and the Institute for Nuclear and Energy Technologies (IKET), both at the Karlsruhe Institute of Technology (KIT). Research is embedded in the Center for Disaster Management and Risk Reduction Technology (CEDIM), a joint venture between the Helmholtz Centre Potsdam- German Research Centre for GeoSciences (GFZ) and KIT. We would like to thank CEDIM as well as the Mannheim Municipal Fire Department as representatives of the city of Mannheim for supporting this work.

REFERENCES

1. Andersson, G. and Donalek, P. (2005) Causes of the 2003 major grid blackouts in North America and Europe, and recommended means to improve system dynamic performance, *Power Systems, IEEE Transaction on*, 20, 4, 1922–1928.
2. Aven T. (2007) A unified framework for risk and vulnerability analysis and management covering both safety and security, *Reliability Engineering and System Safety*, 92, 745-754.
3. Berizzi, A. (2004) The Italian 2003 blackout, *Power Engineering Society General Meeting, 2004. IEEE*, 2, 1673-1679.
4. Bertsch, V. (2008) Uncertainty handling in multi-attribute decision support for industrial risk management, Universitätsverlag Karlsruhe, Karlsruhe.
5. Birkmann, J. (2006) Measuring vulnerability to natural hazards: towards disaster resilient societies, United Nations University Press.
6. Cardona, O.D. (2004) The need for rethinking the concepts of vulnerability and risk from a holistic perspective: a necessary review and criticism for effective risk management, *Bankoff, G., Frerks, G., Hilhorst, D. (Eds.), Mapping Vulnerability: Disasters, Development and People*, Earthscan Publishers, London
7. CEDIM (2012) CEDIM FDA-Report on Hurricane Sandy 22-30 October 2012, available at http://www.cedim.de/english/Hurricane_Sandy.php, (last accessed on 13th November 2012)
8. Corwin, J.L. and Miles, W.T. (1978) Impact Assessment of the 1977 New York City Blackout, Palo Alto, Systems Control Inc. Typed ms. Prepared for Lester H. Fink, Div. of Electric Energy Systems, U.S. Department of Energy.
9. Chang, C.-L. and Chao, Y.-C. (2012) Using the analytical hierarchy process to assess the environmental vulnerabilities of basins in Taiwan, *Environmental Monitoring and Assessment*, 184, 5, 2939-2945.
10. Delfino, B., Massucco, S., Morini, A., Scalera, P. and Silvestro, F. (2001) Implementation and comparison of different under frequency load-shedding schemes, *Power Engineering Society Summer Meeting, 2001*, 1, 307–312.
11. Dong, M., Lou, C. and Wong, C. (2008) Adaptive under-frequency load shedding, *Tsinghua Science & Technology*, 13, 6, 823–828.
12. Fekete, A., Lauwe, P. and Geier, W. (2012) Risk management goals and identification of critical infrastructures, *International Journal of Critical Infrastructures*, 8, 4, 336-353
13. French, S. (2003) Modelling, making inferences and making decisions: The roles of sensitivity analysis, *TOP*, 11, 2, 229-251.
14. German Federal Ministry of the Interior (2010) National Strategy for Critical Infrastructure Protection (CIP Strategy).
15. Girgis, A. A. and Mathure, S. (2010) Application of active power sensitivity to frequency and voltage variations on load shedding, *Electric Power Systems Research*, 80, 3, 306–310.
16. Gronau, N., Röchert-Voigt, T. and Proske, N. (2011) Knowledge management for the protection of critical infrastructures, *Guarascio M., Reniers G.; Brebbia C. A.; Garzia F. (Eds.): Safety and Security Engineering*

IV, Southampton: WITPress, 13-21.

17. Haidar, A. M. A., Mohamed, A. and Hussain, A. (2010) Vulnerability control of large scale interconnected power system using neuro-fuzzy load shedding approach, *Expert Systems with Applications*, 37, 4, 3171–3176.
18. Haidar, A. M. A., Mohamed, A. and Milano, F. (2010) A computational intelligence-based suite for vulnerability assessment of electrical power systems, *Simulation Modelling Practice and Theory*, 18, 5, 533–546.
19. Hernantes, J., Labaka, L., Laugé, A. and Sarriegi, J. M. (2012) Group Model Building: A collaborative modelling methodology applied to Critical Infrastructure Protection, International Journal of Organisational Design and Engineering 2(1): 41-60.
20. Hiete, M. and Merz, M. (2009) An indicator framework to assess the vulnerability of industrial sectors against indirect disaster losses, *Proceedings of the 6th ISCRAM Conference*, Gothenburg.
21. Merz, M. (2011) Entwicklung einer indikatorenbasierten Methodik zur Vulnerabilitätsanalyse für die Bewertung von Risiken in der industriellen Produktion, KIT Scientific Publishing, Karlsruhe.
22. Merz, M., Hiete, M., Comes, T. and Schultmann, F. (2012) A composite indicator model to assess natural disaster risks in industry on a spatial level**,** *Journal of Risk Research*.
23. Mostafa, M. A., El-Hawary, M. E., Mbamalu, G.A.N., Mansour, M.M., El-Nagar, K.M. and El-Arabaty, A.M. (1996) Effects of prioritizing demand on optimal load shedding policy, *International Journal of Electrical Power & Energy Systems*, 18, 7, 415–424.
24. Özyurt, G., Ergin, A. and Baykal, C. (2011) Coastal vulnerability assessment to sea level rise integrated with analytical hierarchy process, *Costal Engineering Proceedings*, 1, 32.
25. Praktiknjo, A., Hähnel, A. and Erdmann, G.(2011) Assessing energy supply security: Outage cost in private households, *Energy Policy* 39, 12, 7825-7833.
26. Raskob, W., Tufte, L., Gers, E., Meyer-zu-Drewer, P., Möllmann, S. and Stärk, K. (2011) SECURITY2People – Features and Experience with the First Demonstrator of an Integrated Disaster Management System, *6th Future Security Conference*, Berlin.
27. Rinaldi, S. M. (2004) Modeling and simulating critical infrastructures and their interdependencies, *Proceedings of the 37th Annual Hawaii International Conference on System Sciences 2004*.
28. Rudez, U. and Mihalic, R. (2011) A novel approach to underfrequency load shedding, *Electric Power Systems Research*, 81, 2, 636–643.
29. Song, H. and Kezunovic, M. (2007) A new analysis method for early detection and prevention of cascading events, *Electric Power Systems Research*, 77, 8, 1132–1142.
30. Triantaphyllou, E. (2000) Multi-criteria decision making methods: a comparative study, A*pplied optimization; 44*, Kluwer, Dordrecht.
31. van der Vleuten, E. and Lagendijk, V. (2010) Transnational infrastructure vulnerability: The historical shaping of the 2006 European "Blackout", *Energy Policy*, 38, 4, 2042–2052.
32. Wiedenhöfer, T., Reuter, C., Ley, B. and Pipek, V., (2009) Inter-Organizational Crisis Management Infrastructures for Electrical Power Breakdowns, *Proceedings of the 6th ISCRAM Conference*, Lisbon.