Critical Infrastructure Resilience: A Framework for Considering Micro and Macro Observation Levels

Florian Brauner
Cologne University of Applied Sciences
florian.brauner@fh-koeln.de

Thomas Münzberg
Karlsruhe Institute of Technology
thomas.muenzberg@kit.edu

Marcus Wiens
Karlsruhe Institute of Technology
marcus.wiens@kit.edu

Frank Fiedrich
Bergische Universität Wuppertal
fiedrich@uni-wuppertal.de

Alex Lechleuthner
Cologne University of Applied Sciences
alex.lechleuthner@fh-koeln.de

Frank Schultmann
Karlsruhe Institute of Technology
frank.schultmann@kit.edu

ABSTRACT

The resilience mechanisms of Critical Infrastructures (CIs) are often hard to understand due to system complexity. With rising research interest, models are developed to reduce this complexity. However, these models imply reductions and limitations. According to the level of observation, models either focus on effects in a CI system or on effects in a single CI. In cases of limited resources, such limitations exclude some considerations of crisis interventions, which could be identified in combining both observation levels. To overcome these restrictions, we propose a two-step framework which enables to analyze the vulnerability of a CI and as well in comparison to other CIs. This enhances the understanding of temporal crisis impacts on the overall performance of the supply, and the crisis preparations in each CI can be assessed. The framework is applied to the demonstrating example of the functionalities of hospitals that are potentially suffering from a power outage.

Keywords

Benchmark, multi-attribute value theory, power outages, time-dependent indicator, vulnerability assessment

INTRODUCTION

Multiple Critical Infrastructure models and frameworks which address different types and levels of observation can be found in the literature. Often, the models intend to provide a continued supply of services or products in crisis situations with a focus either at the business continuity of a single CI (micro-focused models, see e.g. Lindström, Samuelsson, and Hägerfors, 1992) or on the overall provision of vital services and products in a considered district (macro-focused models, see e.g. Chang, McDaniels, Mikawoz, and Peterson, 2007).

These reductions imply boundaries in identifying and assessing appropriate crisis intervention alternatives. In micro-focused models, effects of the CI system which the considered CI is part of, are excluded. A system analysis regarding the comprehensive consequences of the supply for a population in a district is not possible. Macro-focused models regularly reduce complexity by simplifying CI characteristics and, hence, individual aspects of structures and circumstances are neglected. If such limitations are not taken into account by decision makers, a distorted perception and misjudgment of alternatives may occur.

To improve crisis management, a framework design is requested which allows crossing these boundaries. For this purpose, we introduce a two-step analysis framework to conduct a vulnerability assessment. The first step of the framework is micro-CI-orientated and focused on the vulnerability of the organizational units within a specific CI. The organizational units are defined as specific section and their operation/service in the structure itself (e.g. intensive care unit in a hospital). The second step is macro-CI-orientated and addresses the different relevancies of CIs of the same type in a district (comparison of CI among each other). We demonstrate that both steps combined provide enhanced insights into CIs resilience by considering different observation levels. Furthermore, we critically discuss on further research directions of our research in progress.

The paper is structured as follows: In the first section, we outline the objectives and the general principle of the framework proposed. A short introduction is given of the used methods of multi-attribute value theory (MAVT) and benchmark. For demonstrating purposes, we apply the framework to a fictitious example which we briefly introduce in the second section. This is followed by a detailed explanation of the single steps for a micro-CI-vulnerability analysis (third section) and a macro-CI-vulnerability analysis (fourth section). We conclude with a critical remark and outlook in the fifth section.

A FRAMEWORK FOR CROSSING OBSERVERTATION LEVEL BOUNDARIES

To bridge observation boundaries and enhance the understanding of the stress and resilience of a CI in a district, the individual CI structure with all its organizational units and the different importance of a CI in the CI system need to be considered. For this purpose, we distinguish between a micro-CI and macro-CI view on vulnerability (see Figure 1).

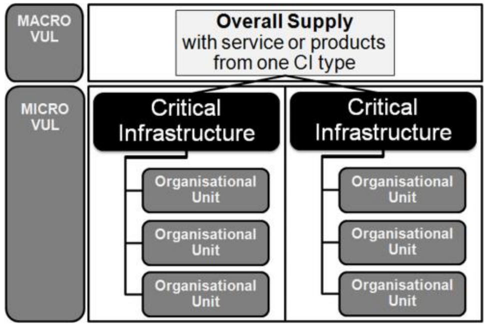

Figure 1. The principle of the analysis framework.

The micro-CI-vulnerability addresses the organizational units within a CI organization. It aims at providing more insights into the influence of the different organizational units of a CI and their role in providing business continuity. The analysis results considering micro-CI-vulnerability should enable decision makers to identify the most vulnerable organizational units of their CI.

For doing so, we propose an adopted multi-attribute value theory (MAVT) to consider the different relevancies of organizational units of a CI and the time-depending effects of coping capacities in each organizational unit.

MAVT (Keeney and Raiffa, 1993) is a well-established analytical method in crisis management (related e.g. are Geldermann, Bertsch, Treitz, French, Papamichail, and Hämäläinen, 2009; Comes, Schätter, and Schultmann, 2013; Möhrle, 2014). We methodologically expand this method by a time-dependent attribute which allows considering the dynamic effects of coping capacities.

Furthermore, CIs of the same type (e.g. hospitals) regularly vary in size and importance in providing services or products. These interdependencies are often neglected, but important for e.g. authorities who are interested in keeping a supply as continuous as possible. These differences are considered by a macro-CI-vulnerability. The macro-CI-vulnerability considers the whole CI structures in a district. It aims at providing insights into the CI importance in providing a vital service or product. We call this the vulnerability in dependency of the supply and demand development through a crisis. To conduct this analysis, we use a benchmark to compare the performances of the organizations among each other. The literature describes several benchmark approaches (e.g. an overview is provided by Schuëller and Pradlwarter, 2007). All systems have an analysis of processes or values according to a reference value in common to assess the current status in comparison to an objective. The analysis can be executed in a qualitative as well as quantitative manner. The benchmark reveals a performance index which can be interpreted as vulnerabilities of weak processes (Piegorsch, Cutter, and Hardisty, 2007).

FICTITIOUS EXAMPLE

For demonstrating purposes, we apply the two-step framework to the fictitious example of three hospitals in a district which are equally affected by a power outage. Power outages in hospitals are critical disturbances which may lead to serious adverse effects if hospital service cannot be ensured. To cope with a power outage in a hospital, all biomedical equipment is able to buffer short-term power outages. In addition, hospitals are provided with emergency power units to ensure critical processes like surgeries, intensive care, etc. for a limited period of time. Due to these preparation and coping capacities, we assume that the organizational units of a hospital have different capabilities for business continuation, which depends on fuel supply or battery capacity. The more of these coping capacities are consumed, the more the vulnerability to suffer from service disturbance increases.

Hospitals differ, for instance, in coping capacities and structural size. Hence, they have not the same potential in providing hospital services in a district. This is particularly relevant in situations where resources like fuel or further selection decisions are requested (e.g. distribution of mobile power units). In this case, crisis management has to concentrate on continuation of the services of the most important hospitals (prioritization).

MICRO-CI-VULNERABILITY ANALYSIS: HOSPITAL LEVEL

A hospital h_a with $(a = 1, \dots, b)$ consists of multiple organizational units $\mathrm{u}_{\mathrm{a,i}}$ with $(i = 1, \dots, l)$. Each unit has different coping capacities and different influences or roles in providing the hospital service. To analyze the micro-CI-vulnerability of a hospital, we extend MAVT by the time-dependent attribute $C_{i,a}(t)$ to consider effects of different coping capacities. In addition, we use a weighting coefficient to take into account the different organizational influences on the hospital service.

The coping capacity of an organizational unit indicates the duration in which business can be continued during a power outage. This duration is derived from $t_c^{i,a}$, which represents the point of time when the coping capacity of an organizational unit is fully consumed, and t_0 as point in time where a power outage starts: $\Delta t^{i,a} = t_c^{i,a} - t_0$.

In this period, vulnerability of the organizational unit increases because less time is available before a unit suffers a power outage. For each organizational unit, we define a $C_{i,a}(t)$ with t for the point in time during a power outage. The vulnerability increase can be determined in different ways e.g., linearly, exponentially, and polynomially. For demonstrating purposes, we use the exponential function adopted from Kirkwood (1996):

$$\mathrm{C_{i,a}(t)} = \begin{cases} \dfrac{e^{\frac{t - t_0 / t_c^{i,a} - t_0}{0,2}}}{e^5} & \text{if } t \leq t_c^{i,a}. \\ 1 & \text{else} \end{cases}$$

The influences are considered by individual weighting coefficients $w_{i,a}$. Various weighting processes are available in the literature e.g., direct weighting or the analytical hierarchical process. We use an easy and practical expert value analysis according to Baumgarten, Brauner, Bentler, Mudimu, and Lechleuthner (2014). Experts from the hospital weigh all organizational units among each other. Two points are given for a very important unit and zero points for less importance. If both organizational units have the same importance, one point is set. The points achieved (subtotals) are divided through

Expert Value Assessment	Emergency Room	Operation Area	Intensive Care Units	Hospital Wards	Subtotal	Weighting coefficients $w_{i,a}$		Coping Capacities $\Delta t^{i,a}$
Emergency Room	X	2	1	1	4	**0.333**	$w_{1,1}$	**72h**
Operation Area	1	X	0	0	1	**0.083**	$w_{2,1}$	**12h**
Intensive Care Units	1	2	X	0	3	**0.250**	$w_{3,1}$	**48h**
Hospital Wards	1	2	1	X	4	**0.333**	$w_{4,1}$	**24h**
				Total	12	1		

Figure 2. Estimated weighting coefficients for four organizational units of a hospital.

the total to derive the weighting coefficient $w_{i,a}$. Figure 2 shows fictitious results for four organizational units of one hospital. The organizational units serve as an examples derived from the German national recommendation for hospital crisis preparedness by Kammel and Schneppenheim (2008).

Based on the MAVT method, we determine the micro-vulnerability $MicroV_a(t_x)$ for a hospital h_a by a sum of all individually weighted time-dependent coping capacity attributes of the organizational units: $MicroV_a(t) = \sum_{i=1}^{l} w_{i,a}\, C_{i,a}(t)$.

Using the values displayed in Figure 2, the vulnerability increases of each organizational unit of a hospital can be illustrated as a vulnerability profile as shown in Figure 3. The diagram shows how the vulnerability of each organizational unit changes in time. The comparison of the values provides useful insights into the roles of each unit and the possible continuation. This allows an appropriate concentration on units which may suffer from power outages earlier than others or have higher influence to the hospital service.

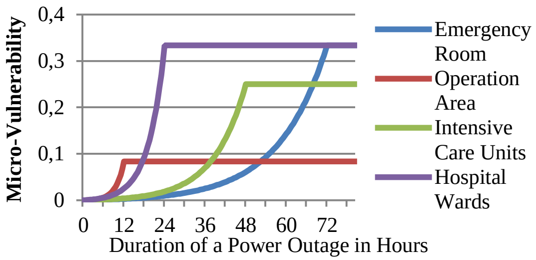

Figure 3. Exemplary result of the micro-CI-vulnerability analysis.

MACRO-CI-VULNERABILITY ANALYSIS: DISTRICT LEVEL

The hospitals vary in size and have different relevancies in providing the overall health services in a district (e.g. University Hospital = focus on emergencies). The macro-CI-vulnerability depends on different aspects like structure, performance, and supply.

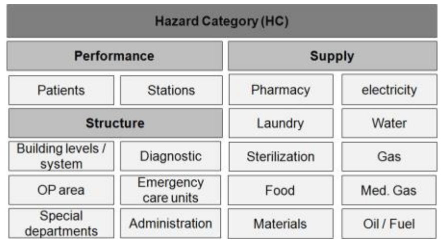

Figure 4. Considered aspects in the questionnaire of the benchmark.

The different aspects have to be collected and fused together in terms of their performance in the scenario of a power outage. In 2007, Piegorsch et al. explained that a benchmark analysis can be useful to estimate the vulnerability in a system. To compare the vulnerability of different hospitals, we introduce a benchmark-MAVT approach which is based on common hazard categories. The hazard categories are comparable factors in every hospital and represent the “process requirements” which have to be more or less fulfilled to keep the organizational units functioning. A questionnaire allows the decision makers in hospitals to classify the own characteristics into categories and score these factors. In the questionnaire, each category is qualitatively described and can be assigned to one of three statements which are scored between one and three points (e.g. supply pharmacy – 1P: stock of basic drugs for 72h; 2P: further stock of medicaments for special treatments; 3P: guaranteed additional drug delivery through crisis). The division of the sum of the collected points through the maximum leads to a normalized hazard category HC_a for each hospital. This approach has already been tested in public transportation systems (see Brauner, Baumgarten, Kornmayer, Bentler, Mudimu, and Lechleuthner, 2014).

The HC_a represents a comparison index of the hospitals and allows a comparison among them at t_0 before the crisis. It does not consider any dynamic changes caused through coping capacities.

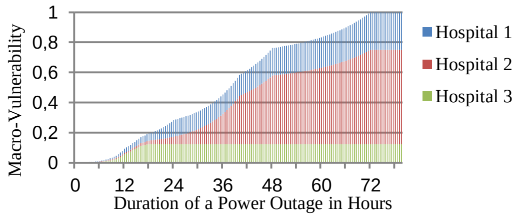

Figure 5. Exemplary result of a macro-CI-vulnerability analysis.

Using MAVT, the multiplication of HC_a and the time-dependent micro-vulnerability of each hospital, generates a macro-vulnerability profile which allows an enhanced insight into the hospitals' situation taking into account their relevancies in providing hospital services in a district: $MacroV(t) = \sum_{a=1}^{b} MicroV_a(t)\, HC_a$

By way of example, we applied the macro-vulnerability analysis to a district with three different hospitals. The results are displayed in Figure 5, which illustrates the increase in the vulnerability of the hospitals.

CRITICAL REMARK AND CONCLUSION

Based on the example of three hospitals, we demonstrated the principle of our proposed two-step framework. The understanding of CI resilience is enhanced by the vulnerability assessment proposed which overcomes the boundaries on the resilience of hospital services. The assessment shows, how long each hospital can ensure business continuation and which CIs are of higher importance than others in a district. Furthermore, detailed insights into the organizational units in each hospital are possible which allows reviewing the resilience. In the case of a crisis and limited resources, the contribution allows comparing multiple interventions that focus on enhancing the resilience of (1) single hospitals in a district, (2) single organizational units in hospitals (3) or both.

Besides these relevant implications for crisis management, there are also some limitations. To demonstrate the basics of the vulnerability assessment, we applied the well-established methods of MAVT and benchmarks. In our further research, we will conduct sensitivity analyses to research the robustness of the comparison. Additionally, we are interested in considering the benefits of other methods like system dynamics or agent-based modeling which allow taking into account CI interdependencies. For the moment, we focused on a rather limited number of CIs and data points which are considered as attributes and benchmarks. The currently used methods allow analyzing the effects of coping capacities regarding the continued supply.

The impacts of sequentially implemented interactions that are realized at different points in time of a power outage are not considered yet, as well as the question how long a CI can operate without certain processes. Another neglected aspect is the definition of resilience which includes CI capabilities to recover from a stress like power outage. All these aspects would also be of interest to future research.

ACKNOWLEDGMENTS

Parts of the presented research were financially supported by the Helmholtz Association and are embedded in its portfolio topic on security research. We are grateful for this support. In addition, we thank Prof. A. Lechleuthner, Medical Director of Emergency Medical Services of the City of Cologne, Germany, for his great collaboration and dedicated support.

REFERENCES

1. Baumgarten, C., Brauner, F., Bentler, C., Mudimu, O.A., and Lechleuthner, A. (2014) A methodology to compare risk management (RM) systems for the application and validation of specific threats in public transportation. *RISK ANALYSIS IX*, 47, 219-228.
2. Brauner, F., Baumgarten, C., Kornmayer, T., Bentler, C., Mudimu, O.A., and Lechleuthner, A. (2014) A Methodology for a vulnerability analysis of public transportation systems in context of terrorist attacks. *9th Future Security, Security Research Conference*; Berlin, Germany.
3. Chang, S.E., McDaniels, T.L., Mikawoz, J., and Peterson, K. (2007) Infrastructure failure interdependencies in extreme events: power outage consequences in the 1998 Ice Storm. *Natural Hazards*, 41, 2, 337-358.
4. Comes, T., Schätter, F., and Schultmann F. (2013) Building robust supply networks for effective and efficient disaster response, *ISCRAM 2013*

Conference Proceedings, Baden-Baden, Germany.

5. Geldermann, J., Bertsch, V., Treitz, M., French, S., Papamichail, K.N, and Hämäläinen, R.P. (2009) Multi-Criteria Decision Support and Evaluation of Strategies for Nuclear Remediation Management, *IJMS*, 37, 238-251.
6. Kammel, P. and Schneppenheim U.W. (2008) Einführung in die Alarm- und Einsatzplanung, *Leitfaden Krankenhausalarmplanung*, 159-200.
7. Keeney, R.L. and Raiffa, H. (1993) Decisions with multiple objectives: Preferences and value tradeoffs, Cambridge University Press, New York.
8. Kirkwood, C.W. (1996) Strategic Decision Making: Multiobjective Decision Analysis with Spreadsheets, Duxbary Press, USA.
9. Lindström, J., Samuelsson, S., Hägerfors, A. (1992) Business continuity planning methodology. *Dis Prev and Mgt*, 19, 2, 243-255.
10. Moehrle, S. (2014) On the Assessment of Disaster Management Strategies, *ISCRAM 2014 Conference Proceedings*, State College, USA.
11. Pederson, P., Dudenhoeffer, D., Hartley, S. and Permann, M. (2006) Critical Infrastructure Interdependency Modeling: A Survey of U.S. and International Research, *Idaho National Laboratory*, INL/EXT-06-11464, Idaho.
12. Piegorsch, W., Cutter, S.L., and Hardisty, F. (2007) Benchmark Analysis for quantifying Urban Vulnerability to Terrorist Incidents, *Risk Analysis*, 27, 6.
13. Schuëller, G.I. and Pradlwarter, H.J. (2007) Benchmark study on reliability estimation in higher dimensions of structural systems – An overview. *Structural Safety*, 29, 3, 167–182.
14.