An Indicator Framework to Assess the Vulnerability of Industrial Sectors against Indirect Disaster Losses

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ABSTRACT

Natural and man-made hazards may affect industrial production sites by both direct losses (due to physical damage to assets and buildings) and indirect losses (production losses). Indirect losses, e.g. from production downtimes, can exceed direct losses multiple times. Thus, the vulnerability of industrial sectors to indirect losses is an important component of risk and its determination is an important part within risk analysis. In this paper a conceptual indicator framework is presented which allows to assess the indirect vulnerability of industrial sectors to different types of disasters in a quantitative manner. The results are useful for information sharing and decision making in crisis management and emergency planning (mitigation measures, business continuity planning), since the developed indicator system helps to take the complex phenomenon of industrial vulnerability and the underlying interdependencies into account. Besides the identification and conceptual motivation of the indicators, methodical aspects such as standardization, weighting and aggregation are addressed.

Keywords

Indicators, Industrial Crisis Management, Industrial Vulnerability Assessment, Decision Support

INTRODUCTION

Natural and man-made disasters such as floods, earthquakes, storms, terrorist attacks or industrial incidents do not only affect people and the environment but also infrastructures and industrial companies. Various disasters in the recent past such as Sumatran Earthquake and Tsunami, 2004 and Hurricane Katrina, 2005, have shown that extreme events may constitute a high risk to industrial production sites and networks (Kleindorfer and Germaine, 2005; Zsidisin et al., 2003).

Within disaster risk management the term "risk" is usually defined as a loss that occurs with a given probability (Crichton, 1999; Kaplan and Garrick, 1981). In the standard conceptual framework risk is a product of hazard (*H*), vulnerability (*V*) and exposure (*E*) (Cardona, 2004; Carreno, Cardano and Barbat, 2006):

$$R = E \times H \times V \tag{1}$$

Here the hazard H is described by its severity and probability. The exposure E represents the number and values of elements at risk. The understanding of vulnerability V is very broad and current literature encompasses many different definitions, concepts and methods to systemize vulnerability (Birkmann, 2007; Cutter, 2003). Villagran de Leon (2006) defines *vulnerability as the predisposition of an element or a system to be affected or susceptible to damage*. A very similar definition, but with particular focus on the social susceptibility, is given by Borden, Schmidtlein, Emrich, Piegorsch, and Cutter, (2007). The vulnerability of industry has two dimensions, direct damages and indirect damages (Table 1). In industrial production sites direct losses are mainly caused by the partial or total damage of buildings, production equipment and piping as well as service and control installations (Geldermann, Merz, Bertsch, Hiete, Rentz, Seifert, Thieken, Borst, and Werner, 2008). In some industrial sectors disasters may induce also *direct* secondary damages (Cruz and Okada, 2008). Here the chemical industry takes an exceptional position since natural disasters may cause the release of hazardous substances which may result in severe environmental pollution, explosions, fires and threats to employees.

These so-called natural hazard-triggered technological disasters (Natechs) are relatively rare, but the social as well as the environmental consequences of such events can be devastating (Cruz and Okada, 2008).

Indirect losses include all economic losses which are induced by a loss of production (primary indirect losses) and negative market effects in the aftermath of a disaster (secondary indirect losses). Production losses are mainly influenced by the duration of the production downtime. Production losses may result from direct damages, supply chain interruptions and outages within critical infrastructure. Negative market effects caused by a catastrophic event comprise e.g. the general rise of material prices in the affected region, competitive disadvantages over non-affected competitors and an overall damage to the company's reputation. In some industrial sectors the indirect losses can be in the order of three to ten times larger than direct losses (Kleindorfer and Germaine, 2005). Therefore, within risk analysis it is essential to pay particular attention to the quantification of the vulnerability to indirect disaster losses. While currently mainly direct vulnerabilities are assessed (e.g. Penning-Rowsell, Johnson, Tunstall, Tapsell, Morris, Chatterton, and Green, 2005; Rose and Lim, 2002; Seifert, Thieken, Merz, Borst, and Werner, (accepted)) sophisticated methods to evaluate indirect disaster vulnerabilities are rare. Within this paper we focus on the assessment of primary indirect losses and here in particular the vulnerability to production losses caused by disasters.

Direct Losses	**Indirect losses**
Primary direct losses	**Primary losses**
Physical damage to buildings	Loss of production due to direct damages
Physical damage to production equipment	Loss of production due to infrastructure disruptions
Physical damage to raw materials	Loss of production due to supply chain disruptions
Physical damage to products in stock	
Physical damage to semi-finished products	**Secondary losses**
Physical damage to control installations	Market disturbances (e.g. from higher prices for raw materials)
Physical damage to service installations	Decreased competiveness
Secondary direct losses	Damage to company's image
Secondary hazards and damages (e.g. due to explosions)	Extra labor for process recovery
Costs for remediation and emergency measures	

Table 1: Types and Origin of Industrial Disaster Losses

The indirect vulnerability of production systems is influenced by various factors and system characteristics, such as technical attributes, organizational properties and the degree of external dependencies (e.g. dependency on critical infrastructures). Furthermore, when analyzing industries it is not reasonable to analyse only single industrial companies, since due to the global interlacement of modern production systems the company vulnerability should be assessed in a network context (Rose and Lim, 2002). Due to these complex structures and the high the degree of dependencies, assessing the indirect vulnerability of industrial production sites and sectors is not trivial. Nevertheless, as vulnerability is an important component of risk this assessment is an essential step within risk analysis and in the end a prerequisite for risk reduction and emergency preparedness. This is because risk analysis and especially vulnerability assessment help to evaluate the potential consequences of disasters and to identify particularly weak points within a system (Birkmann, 2006).

As described above, due to the complex phenomenon of vulnerability, the measurement of vulnerability (and especially its social and economic component) can be challenging (Brooks, Adger, Kelly, 2005). In the field of natural disaster risk assessment one methodology to evaluate the vulnerability of regions is the use of indicator approaches (Adger, 1999; Cardona, 2006; Dilley, Chen, Deichmann, Lerner-Lam, and Arnold, 2005; Pelling, 2004; Perduzzi, 2006). Within a comprehensive indicator framework, Cardona (2005) developed the Prevalent Vulnerability Index (PVI). This index considers three main factors influencing vulnerability (1) exposure and physical susceptibility, (2) socioeconomic fragility and (3) lack of resilience. The social vulnerability index (SoVI), created by Cutter, Boruff and Shirley (2003), enables the analysis of the spatial patterns of the social vulnerability on an US-County level (Cutter and Finch, 2008) as well as on the city level (Borden et al., 2007). The SoVI incorporates 11 components contributing to a regional social vulnerability and may be viewed as an algorithm for quantifying social vulnerability rather than as a simple numerical index (Schmidtlein, Deutsch, Piegorsch and Cutter et al, 2008). However, a methodology for the assessment of the indirect vulnerability of industrial sectors to natural disasters or other extreme events is currently missing.

Within this paper we present the development of a conceptual indicator framework for indirect vulnerability assessment of different industrial sectors to disasters. This approach involves the determination of the relative vulnerability of industrial sectors via indicators and enables the analysis of the complex structures and dependencies often found in industry. The benefit of the methodology is twofold. Firstly, the results can be used to compare different industrial sectors with regard to their indirect loss potential (comparison of one overall-value of vulnerability). Secondly, the structured analysis of factors influencing vulnerability and underlying interdependencies (which are the source of vulnerability) helps to better understand the complex phenomenon of industrial vulnerability (contribution of the sub-indicators to overall vulnerability). Therefore, on a company level, the outcomes will also allow to identify highly vulnerable processes, flows and assets. This is an important requirement for decision making and information sharing in the field of industrial crisis management and emergency planning (e. g. business continuity planning). Furthermore, it is envisaged to integrate the sectoral vulnerability analysis later into a larger indicator framework (cf. "expected results and future working directions"). Since this framework aims at assessing the overall disaster vulnerability (social, industrial, environmental) of different regions in Germany, the sectoral indicator framework is an important foundation for the assessment of the spatial distribution of the industrial vulnerability. In the end, the results of the regional vulnerability assessment can be used by governmental decision makers for the development of place-based emergency plans, recovery measures and vulnerability reduction strategies.

The paper is organized as follows: In the next section we provide some background information on indicator approaches, definitions and the application of indicators in vulnerability and risk analysis. In the third section some theoretical fundamentals of indicator development are presented and an overview on the conceptual framework for the assessment of indirect vulnerability is given. We then provide some information on methodological aspects in indicator development (e.g. weighting, standardization and aggregation). Finally, we conclude with a discussion of the expected results, the implications of the developed methodology and directions for future research.

INDICATORS AND DECISION MAKING

Indicators are broadly used in economic, social and environmental analysis (Adger, 1999; Birkmann, 2006; Cutter et al. 2003). In recent years especially the use of sustainability indicators has emerged (Bebbington, 2007). A general, but comprehensive definition for indicators is given by Gallopin (1997) who defines *indicators as variables (not values) which are an operational representation of an attribute, such as quality or/and characteristics of a system.*

In general, indicators are management tools which describe and operationalize complex system characteristics in a quantitative and transparent way. Therefore, indicator frameworks tend to bridge the gap between theoretical concepts of complex systems and decision making (Gallopin, 1997). This enables a comparative analysis, benchmarking and the support of decision makers in complex decision situations (e.g. in crisis management and emergency planning).

In the field of disaster risk analysis various approaches using indicators for regional vulnerability assessment can be found (Cardona, 2006; Cutter et al 2003; Dilley et al., 2005; Peduzzi, 2006). All theses approaches aim at assessing risk and vulnerability quantitatively by means of indicators in order to compare different regions or communities (Birkmann, 2007; Schmidtlein, 2008). In the context of vulnerability assessment *indicators represent an operational representation of a characteristic or a quality of a system able to provide information regarding the susceptibility, coping capacity and resilience of a system to an impact of a disaster* (Birkmann, 2006). The vulnerability of a system is in general determined by different factors. Therefore, the vulnerability cannot be captured by one single indicator. Instead multi-dimensional concepts, such as composite indicators, are needed to assess the vulnerability of such a system. Composite indicators are formed when individual indicators are compiled to a single index based on an underlying theoretical vulnerability framework (model) (Nardo, Saiana, Saltelli, Tarantola, Hoffmann, and Giovannini, 2005).

In the following we describe the development of a composite vulnerability indicator framework for the assessment of indirect industrial vulnerability. We present the development of the theoretical framework, the identification of appropriate indicators (and sub-indicators), as well as the selection of adequate standardization, weighting and aggregation methods.

DEVELOPEMENT OF AN INDICATOR FRAMEWORK FOR INDIRECT INDUSTRIAL VULNERABILITY ASSESSMENT

Steps in developing an indicator framework

The process of indicator development can be distinguished in different iterative steps. While in the field of environmental assessment Maclaren (1996) defines nine consecutive steps, the OECD handbook on constructing composite indicators differentiates 10 different steps or phases (Nardo et al., 2005). Combining similar steps we attain seven main steps within composite indicator development:

1. Developing a theoretical indicator framework
2. Selecting indicators and sub-indicators
3. Data gathering for selected indicators
4. Standardization
5. Weighting and Aggregation
6. Sensitivity analysis
7. Visualization

As these steps are similar to the main phases of multi-criteria decision analysis (MCDA) (cf. e.g. Belton and Stewart, 2002), some MCDA methods and software solutions can be applied for the development of a composite indicator. In the following we describe the main steps of developing an indicator framework to assess the indirect vulnerability of industrial sectors.

Theoretical indicator framework and indicator selection

The theoretical indicator framework provides the basis for the selection and combination of single sub-indicators into a significant composite indicator. Within this step the potential topics, influencing factors and theoretical dependencies are structured and integrated into a model-like framework (Birkmann, 2006). The theoretical indicator framework should clearly depict what should be assessed and how this is influenced by sub-components. Here, the depiction of existing linkages among the statistically independent influence factors constitutes one of the major challenges. The design of the framework depends on its purpose, the target group and often the availability of data (Birkmann, 2006).

Within the development of a theoretical indicator framework and the selection of appropriate sub-indicators, similar to each modeling process, a trade-off between accuracy and simplification has to be made. On one hand the theoretical, often very complex linkages must be depicted and on the other hand the number of sub-indicators should be low, in order to keep the framework understandable and traceable for decision makers. If the number of determining variables (sub-indicators) becomes too high, statistical methods can be applied. For example, within the above mentioned SoVI, for example, principal component analyses (PCA) is used in order to reduce the number of index variables (Cutter et al. 2003).

The selection of the sub-indicators is influenced by the underlying theoretical indicator framework and quality criteria, which should be followed in the selection process. For example should be measurable, comprehensible, reproducible, comparable, cost effective, relevant and sensitive (for further quality criteria see Birkmann, 2006, and UN/ISDR, 2008).

The composite indicator presented in this paper allows to assess the vulnerability of industrial sectors to primary indirect losses (production losses) caused by natural or man-made disasters. This vulnerability is determined by various factors which can be identified by literature review, review of historical disaster data or expert judgments (Schmidtlein et al., 2008). The detailed procedure used for the selection of indicators and sub-indicators within the presented framework is depicted in figure 1.

Identification of the theoretical vulnerability framework		Indicator selection step	Source
	1	Identification of essential production factors Identification of dependencies Identification of risk factors/determinants of vulnerability	Risk management literature Production science literature Expert judgement
	2	Derivation of measurable variables (sub-indicators)	No additional sources needed
	3	Assignment of sub-indicator values	Statistical Data Expert judgement

Figure 1: Identification of the theoretical framework and selection of indicators

Since for industrial disaster losses historical data are hardly available, literature on production interruptions and industrial risk management as well as literature on production science need to be taken as a basis for the identification of factors influencing the vulnerability of industrial sectors (step (1) in figure 1). This enables the identification of important dependencies and prerequisites for efficient production processes, which if they are missing can be seen as risk factors and determinants of the indirect industrial vulnerability. In step (2) measurable variables which are suitable to represent the identified dependencies and theoretical linkages must be determined. In step (3) the values must be assigned to the sub-indicators using e.g. statistical data, qualitative data (e.g. from literature) or expert judgments (e.g. obtained from moderated workshops). In the following we describe the identification of the theoretical basis and dependencies for the industrial vulnerability framework.

Based on production theory production losses might occur when the production factors (labor, capital, equipment, material etc.) are not available as required, e.g. not in sufficient amount or quality (Hackmann, 2008; Varian, 2004). Furthermore the secured availability of critical infrastructures (Rose, Benavides, Chang, Szesniak and Lim, 1997) and the undisturbed material and information flow within supply chains are essential for the maintenance of production processes (Rose and Lim, 2002; Wagner and Bode, 2006; Yoshida and Deyle, 2005;). Based on this the sub-indicators identified to assess the indirect industrial vulnerability can be grouped into 3 main types: indicators for input factor dependency, for infrastructure dependency and for supply chain dependency. In total 15 factors (sub-indicators) influencing the vulnerability of industrial sectors have been identified. The hierarchical indicator framework is depicted in Figure 2.

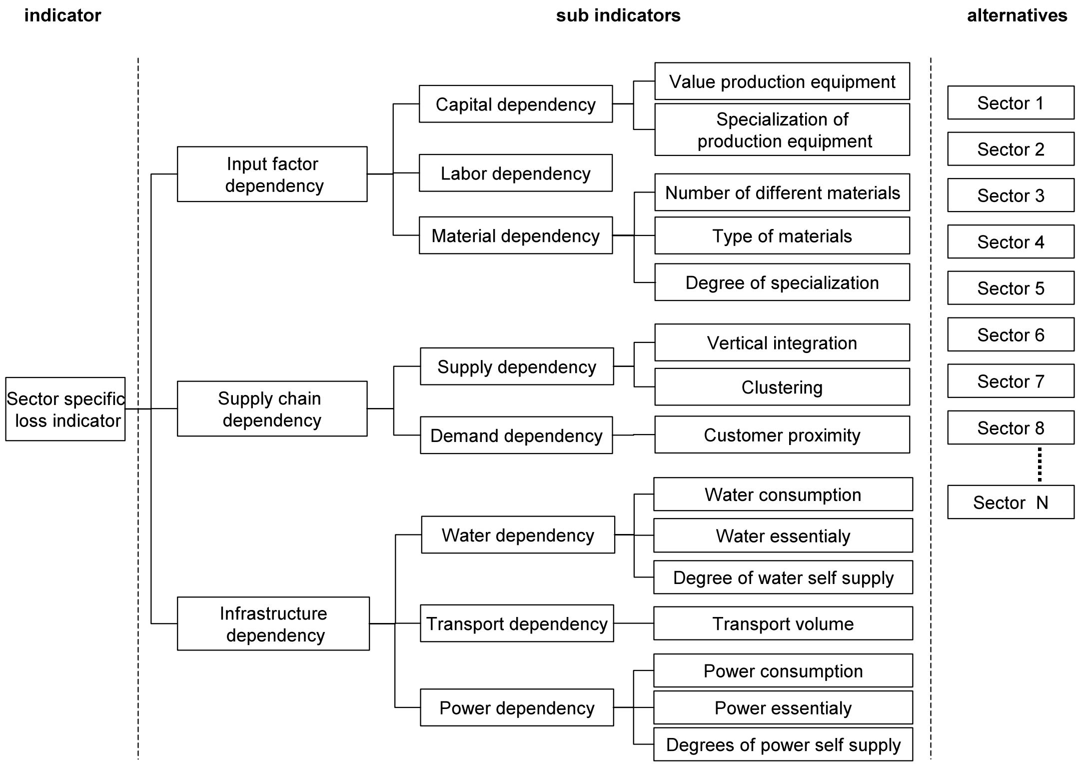

Figure 2: Hierarchical indicator framework

The proposed set of indicators takes into account that industrial sectors with a high capital demand (in terms of machinery and equipment, “value production equipment”) and extensive material requirements might be hit harder by disasters than sectors with minor requirements. The “degree of specialization” of the production equipment plays an important role, since in case of direct asset damage more specialized equipment is more difficult to replace and therefore longer production downtimes are likely. Regarding the material criticality the “total number of different materials” needed for the production process, the “type of materials” and the “degree of specialization” of the materials/parts must be considered. Moderate amounts of standard industrial materials/parts can be more easily procured after a disaster than a high amount of specialized materials/parts for which there are only few suppliers (cf. Wagner and Bode, 2006). Thus production downtimes and indirect vulnerability are expected to be higher in case of specialized materials/parts.

Furthermore, the framework takes into account that within industrial sectors which show a high degree of dependency on transportation as well as on water and power supply, extreme events might cause severe production losses due to the interruption of critical infrastructures (Jiang, Tatano, Kuzuha, Matsuura, 2005; Rose et al., 1997). The water and power dependency of an industrial sector depends on the characteristics of the product and the production process (“power essentiality”) (Zhang, Lindell, Prater, 2008). Furthermore the amount of water and electric power needed (“power resp. water consumption”) is important, since in the event of a disaster with subsequent infrastructure disruptions re-establishing “smaller” electric power or water supply systems is supposed to be easier and faster. Finally, a higher degree of water resp. power self supply increases the resilience of industrial companies to disasters with infrastructure disruptions (“power/water self supply”).

Other drivers of the overall indirect vulnerability potential of an industrial sector arise from the characteristics of the supply chain (Yoshida and Deyle, 2005) . Here, structural supply chain characteristics like complexity, density and node criticality play an important role (Falasca, Zobel and Cook et al., 2008). Since these factors are hard to assess on a sectoral level, supply chain design characteristics are expressed via indicators depicting the supply and demand dependencies of the different industrial sectors. For example, an indicator which depicts supply dependency in a very simplified but manageable (using input-output tables) way is the "degree of vertical integration". The assumption made here is that companies with a higher degree of vertical integration need less supply materials and therefore are less susceptible to supply interruptions. However, it is neglected that within industrial production one single missing part can interrupt the whole production process. Another factor which increases indirect disaster risks is regional sourcing and the geographic concentration of suppliers (Zidisin, 2003), we called it "cluster tendency" of a sector. E.g. Steinle and Schiele (2002) give examples for sectors with a tendency to form industrial clusters.

Sector specific indicators are determined for 15 different industrial sectors. This takes into account, that different industrial sectors show different vulnerabilities to disasters according to their structural, organizational and technical characteristics. Furthermore, the indirect vulnerability of systems is disaster depended. For example an industrial production site might be highly vulnerable to floods but relatively resilient to earthquakes. Depicting this hazard specificity in the theoretical framework constitutes another challenge. In a first step we propose to integrate these dependencies by means of different weights (cf. section on weighting of indicators).

Data collection for selected indicators

In this step accurate, reliable and accessible data must be gathered for all sub-indicators identified in the theoretical framework (Birkmann, 2006). In the field of vulnerability assessment of industrial sectors this can be a major problem, due to data privacy and unavailability of data. While for some indicators in Figure 1 (e.g. "power consumption", "water self supply", "degree of vertical integration") statistical data can be used some other sector specific data must be taken from literature (e.g. power resp. water essentiality). For some other indicators no published data can be found so that expert judgment is needed (e.g. for material dependency). Table 2 gives an overview on the data collection method for the different sub-indicators and shows the positive or negative impact on vulnerability of the sub-indicator.

	Sub-indicator	Used data source	Positive (+) or negative (-) impact on vulnerability
Production factor dependency	Value of production equipment	Statistical data	+
	Number of different materials	Literature/experts	+
	Type of materials	Literature/experts	+
	Degree of specialization of materials	Literature/experts	+
Supply chain dependency	Vertical integration	Statistical data	-
	Clustering tendency	Literature/experts	+
	Customer proximity	Literature/experts	-
Infrastructure dependency	Water consumption	Statistical data	+
	Water essentiality	Literature	+
	Degree of water self supply	Statistical data	-
	Transport volume	Statistical data	+
	Power consumption	Statistical data	+
	Power essentiality	Literature	+
	Degree of power self supply	Literature/statistical data	-

Table 2: Overview on data collection methods for the selected sub-indicators

Standardization

Before aggregating the values of the sub-indicators into an overall composite indicator value, the sub-indicator values must be standardized. This is necessary because most of the sub-indicators have different units which therefore cannot be integrated equally into the indicator framework in their original mode. Furthermore, the standardization step enables the integration of quantitative and qualitative sub-indicators within the same framework.

Within this step the values of all *n* sub-indicators are depicted on a scale between 0 and 1 using value functions. A value function has to be defined for each sub-indicator where x_i is the measured value of sub-indicator *i* for industrial sector *a*, by

$$v_i : \begin{cases} \mathrm{R} & \rightarrow [0,1] \\ x_i(a) & \mapsto v_i(x_i(a)). \end{cases} \tag{2}$$

such that 0 stands for a measured value x_i causing lowest and 1 for a value x_i causing highest vulnerability.

There are a number of different standardization methods which are supported by common multi-criteria software tools (e.g. WebHIPRE, Logical Decisions®). A linear value function for a sub-indicator with positive impact on vulnerability can be defined by

$$v_i(x_i(a)) = \frac{x_i(a) - x^i_{\min}}{x^i_{\max} - x^i_{\min}} \tag{3}$$

Where x^i_{min} is the lowest and x^i_{max} the highest sub-indicator value measured throughout all *m* industrial sectors. A higher value of $x_i(a)$ corresponds to a higher indicator specific vulnerability $v_i(x_i(a))$. Similarly, a linear value function for a sub-indicator with negative impact on vulnerability is given by

$$v_i(x_i(a)) = \frac{x^i_{\max} - x_i(a)}{x^i_{\max} - x^i_{\min}} \tag{4}$$

However, value functions do not need to be linear. Often, a nonlinear value function, e.g. an exponential value function, represents the coherence between the measured value and the vulnerability much better (cf. e.g. Bertsch, 2008).

Weighting and aggregation

Another important step is within indicator development is the setting of weights. Weights express in our framework the contribution and relative importance of the individual sub-indicators to the overall indirect vulnerability. The weighting vector $w_i = (w_1 \ldots w_n)$ contains the weights of all *n* sub-indicators. It is important to ensure that w_i satisfy the constraint

$$\sum_{i=1}^{n} w_i = 1 \, . \tag{5}$$

The elicitation of weights requires a deeper understanding of the theoretical vulnerability framework. For example, the weights assigned for the different sub-indicators might change when analyzing different disaster types (e.g. storm, flood). Therefore, the elicitation of weights is ideally done in workshops and group discussions with experts from industry and disaster science. For the identification of weights various methods, such as analytical hierarchy process (AHP), the SWING method, the SMARTER method or DIRECT weighting, have been developed. For comparison and details of the use of the different methods see e.g. Belton and Stewart, 2002 and Bertsch, 2008.

After determining the standardized sub-indicator values and the weights of the different sub-indicators, the overall vulnerability value is calculated (for each analyzed industrial sector). Assuming mutually independent attributes, the standard additive aggregation rule can be used and the overall vulnerability of an industrial sector $V(a)$ can be calculated as (cf. Keeney and Raiffa, 1976)

$$V(a) = \sum_{i=1}^{n} w_i v_i(x_i(a)) \tag{6}$$

EXPECTED RESULTS AND FUTURE WORKING DIRECTIONS

An overall indirect vulnerability indicator for different industrial sectors provides decision makers with a simple quantitative measure for the indirect vulnerability which is complex in nature, influenced by many different factors and therefore generally difficult to capture.

The framework presented here enables a simple comparison of industrial sectors with regard to their indirect vulnerability to disasters. A disaster specific weighting of the sub-indicators allows also to determine differences in indirect vulnerabilities against different types of disasters. The proposed framework can then help to identify particularly susceptible industrial sectors and can support decision makers in determining particularly critical disaster types. In this way it facilitates the risk assessment process and decision making on adequate risk reduction measures and mitigation planning.

The use of multi-criteria decision analysis (MCDA) techniques will facilitate group decision making when determining the weights but also to visualize the contributions of the different sub-indicators (e.g. stacked-bar charts, spider diagrams) and the impact of uncertainties on the overall sectoral vulnerability (cf. Bertsch 2008). This enables the decision makers to identify more easily the critical/vulnerable areas within the individual sector, e.g. power dependency. Knowing this decision makers are able to identify where to set up technical as well as organizational emergency preparedness measures (e.g. Business Continuity Planning).

Figure 3 shows some exemplar results for the calculation of overall vulnerability indices for 15 different industrial sectors as well as results for the sub-indicator “infrastructure dependency”. Since not all sector specific data are available yet, in order to give a working example, some data assumptions have been made and equal weighting of sub-indicators has been applied. Within this example the “Electronics” sector shows the highest overall vulnerability, followed by the “Automobile Industry”, “Consumer Good Production” and “Chemical Industry” (left side of figure 1). While for the former the vulnerability is notably influenced by input factor and supply chain dependencies, within the “Chemical Industry” infrastructure dependency highly contributes to the overall vulnerability. Regarding the sub-indicator “Infrastructure Dependency” (and not the overall vulnerability), it can bee seen that (at least in the shown example) the sector of “Metal Production” shows the highest vulnerability to infrastructure disruptions, followed by the “Chemical Industry” and the “Oil Refining and Petrol Industry” (right side of figure one). Furthermore the single contributions of the different infrastructure dependencies (water, power, transport) can be identified in figure 3.

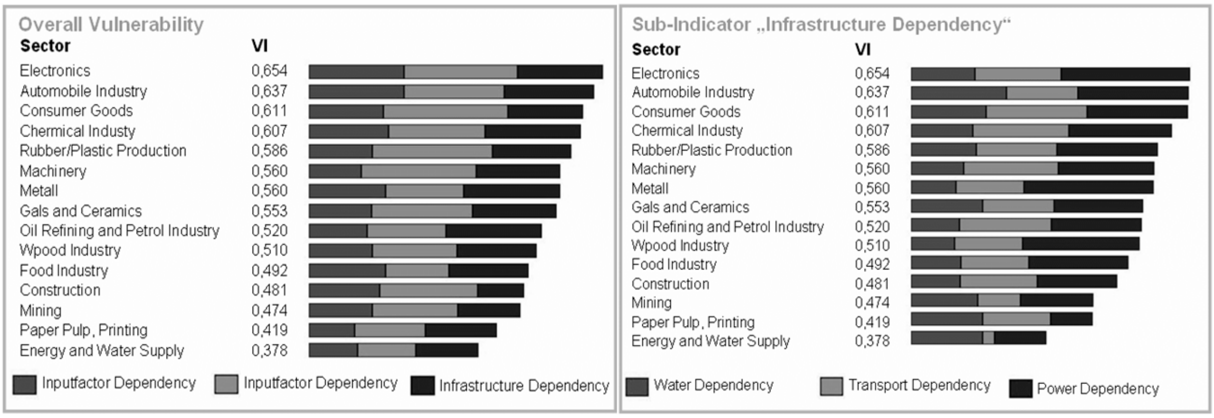

Figure 3: Exemplar results

The work presented here is part of a larger research program of the research group on “vulnerability assessment” of the Center for Disaster Management and Risk Reduction Technology (CEDIM). This group aims at developing an indicator framework to assess the overall indirect disaster vulnerability (social, industrial and environmental) of different European regions. For this purpose the presented indicator framework for assessing indirect vulnerability of industrial sectors will be combined with indicator frameworks for social and environmental vulnerability.

CONCLUSIONS

The main objective of the work presented within this paper is the development of a conceptual methodology for the assessment of the indirect disaster vulnerability (the susceptibility of production losses due to disasters) of different industrial sectors. Assessing indirect disaster vulnerabilities is an important step within the risk assessment and a requirement for effective disaster prevention planning and crisis management as the vulnerability assessment process sheds light on the particularly critical elements of the analyzed industrial sectors. This, is a valuable information for decision making and helps to decide where mitigation and prevention measures are necessary and what the most important action points within crisis management are. However, assessing the vulnerability of industrial production sites and sectors to indirect disaster damages is a major challenge as production losses are influenced by many technical and organizational factors and causal correlations are often very complex.

The indicator framework, presented in this paper, tries to reduce these complexities. The proposed indicator framework helps not only to integrate the relevant critical factors and to depict theoretical coherences but also to depict the results in a transparent and traceable way which is particularly important for decision making in the field of crisis and emergency management. The presented indicator framework focuses on the industrial vulnerability to primary indirect losses (production losses as a result of the unavailability of necessary input factors due to (i) direct disaster losses, (ii) supply chain disruptions, and (iii) critical infrastructure disruptions).

When data collection for the regarded sub-indicators and industrial sectors will be finished, overall indicators for the different sectors will be calculated and the framework will be integrated into a regional disaster vulnerability model. Furthermore, future work will focus on the assessment of uncertainties using MCDA techniques and the implementation of sensitivity analyses.

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