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Mariana Burkhardt

IMPACTS OF NATURAL DISASTERS ON SUPPLY CHAIN PERFORMANCE

KIT Scientific Publishing

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Karlsruher Institut für Technologie (KIT)
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Zur Erlangung des akademischen Grades eines Doktors der Wirtschaftswissenschaften (Dr.rer.pol.) von der KIT-Fakultät für Wirtschaftswissenschaften des Karlsruher Instituts für Technologie (KIT) genehmigte Dissertation

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To Granny

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Karlsruhe, July 2019 *Mariana Burkhardt*

Contents

List of Figures

List of Tables

Acronyms

AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
C	(Tropical) cyclone
CE	Coastal erosion
CH	Coastal hazards
Coef	Coefficient
Coef std err	Coefficient standard error
Conf interval	Confidence interval
Cond No	Condition number
CP	Cold period
G	General
D	Drought
DE	Desertification
DP	Dry period
E	Erosion
EW	Extreme weather
EQ	Earth quake
F	Flood
FF	Forest fire
FMEA	Failure Mode and Effect Analysis
G	General
GHG	Greenhouse Gases
H	Hurricane
HDI	Human Development Index

HP	Hot period
HW	Heat wave
HWI	High winds
HPP	Homogeneous Poisson Process
IDP	Internally displaced people
KPI	Key Performance Indicator
L	Landslide
LDA	Loss Distribution Approach
MAUT	Multi Attribute Utility Theory
MCT	Mean closure time
MPA	Marine protected area
NumObs	Number of observations
NumVar	Number of variables
OCH	Other coastal hazards
PPP	Purchasing power parity
S	Storm
SL	Sea-level rise
SLI	Slide
ST	Sea temperature
T	Tornado
TS	Temperature stress
UNCTAD	United Nations Conference on Trade and Development
VaR	Value at Risk
WP	Wet period

1 Introduction

1.1 Motivation and objective

One of the best known natural disasters with global supply chain effects is the 2011 earthquake followed by a tsunami in Fukushima, Japan. Apart from the tremendous impact and suffering this event caused, especially where the flood wave hit, it also resulted in serious domestic and global supply chain disruptions ([214], p.76). This is not surprising, as Japan is a major worldwide manufacturing hub and the fourth largest export country in the world ([277]). Strongly noticeable had been shortages of critical components, operational shut downs, operations at reduced capacities and price increases for lacking materials ([201]).

Another event that stayed in memory is the volcanic eruption of Eyjafjallajökull 2010 in Iceland (here and following [180], p.93). Due to a massive ash cloud airlines were forced to ground their airplanes and also airports had to close for safety reasons. The event brought therewith a major shift of transport modes for continental freight, from air to rail, road or water transport. Even affected were intercontinental flights, as not all cargo could be rerouted to more southerly airports for reasons of capacity. So especially perishable goods, like flowers and fresh fruits did not find their way to Europe. Even on the other side of the globe the effects were noticeable, as for example in Japan, Nissan had to suspend production lines due to a lack of necessary parts.

As the aforementioned examples show, natural disasters affect businesses and supply chains in a severe manners, while business interruptions are the most frequently observed effect ([306], p.1519). Moreover, these performance impacts hampering normal operations can spread out all over the world and can even raise their magnitude. This is more than valid as through increased interconnectedness and more globalized supply chains local effects proceed from the place of origin to other connected points within the network ([383], p.327; [58], p.6; [115], p.70; [86], p.1116; [79], p.1; [372], p.305). So even businesses that are not directly affected can suffer indirect consequences, e.g. 'due to the failure of their suppliers or difficulties transporting supplies where needed' ([61], p.172).

Apart from those effects observed today, future developments seem even worse, as it is expected that the frequency and magnitude of natural disasters will increase in the next decades ([217], p.1159; [392], p.380; [78], p.90; [114], p.V; [194]), and that due to climate change even weather patterns are suspected to change ([115], p.68). Therefore a supply chain must be designed to meet those future developments, coping with changing environments in an appropriate way ([165], p.645). Thus a sustainable supply chain design takes the positive and negative potentials of a region into consideration ([86], p.1116), but only when the characteristics defining the potential for harm are known, risks can be reduced. And 'as our understanding of those [...] forces improves, so does our chance of developing more robust strategies for preparedness/ planning, response and recovery' ([392], p.381).

To assess the vulnerability of supply chains to natural disaster it is therefore necessary to investigate the attributes of the surrounding environment (the regions or places a supply chain is embedded in), which serve as explaining momentum for differences in vulnerability to natural disasters between distinct locations. The ambient system thereby consists of social, economic, physical and environmental aspects.

Nevertheless, impacts of natural disasters on businesses (performance) respectively supply chains - and so also supply chain vulnerability against natural threats - are relatively understudied, as the focus lies more on people's safety rather than on business continuity ([61], p.169ff; [379], p.103; [381], p.1f; [382], p.54). Also 'empirical observations on how businesses respond after a major catastrophe are rare' ([175], p.1007). But natural disasters 'can and do affect the performance of the supply chain' ([79], p.1), as the aforementioned examples demonstrate. This situation is aggravated by the fact that businesses do relatively little to prepare for catastrophes and if they do, measures are often site-specific, ignoring problems arising from outside the corporation and the aforementioned carry-over effects ([382], p.54). Thus despite the fact that people's safety is 'ranked' higher than business issues this neglect and the increased frequency and intensity of natural disasters can lead to more vulnerable supply chains regarding external threats ([375], p.121). This results in severe supply chain disruptions.

However, current supply chain risk assessment methods mostly lack a consideration of external threats, such as natural disasters, in general. If risks from outside a supply chain network are mentioned, the majority refers to risks associated with suppliers (for example [391]; [167]; [184]; [162] and [103]). That suggests that primarily the location of a supplier defines the vulnerability to natural forces. What also leads to the conclusion that production facilities in risk prone areas bear a high risk for supply chains. On the other hand, like supply chain risk assessments lack the incorporation of natural disasters, country and natural disaster risk approaches lack any consideration of supply chain impacts (for example [38]; [248] and [109]).

The main objective of this work is therefore to develop an approach that assesses the performance impacts of natural disasters on supply chain performance, as none currently exist. To consolidate those findings, an intensive literature review will be conducted. Moreover it is necessary to research the characteristics that build the potential for harm within distinct locations and to explain different levels of susceptibility. A definition of 'performance impacts' is required as well as the identification of an indicator that measures the effects. Based on the results of the developed approach implications for supply chain designs and procurement decisions are given. The development of the approach *SCperformND - **S**upply **C**hain **perform**ance impact assessment of **N**atural **D**isasters* and the necessary steps are explained in the following chapters of this work.

1.2 Structure

In **Chapter 1** the motivation for the topic is firstly given. Raising awareness for the expected increase in frequency and intensity of natural disasters makes it inevitable to take those events also in supply chain risk management into consideration.

Chapter 2 provides an overview on relevant definitions, clarifying risk, supply chain risk, vulnerability and exposure in the context of supply chain and natural disaster risk assessment. Additionally, factors that lead to an increased vulnerability of supply chains are explained. The chapter is concluded with the classification of supply chain risks, once without a concrete focus on natural events (a so called general classification) and otherwise in accordance to external risks. Additionally the risk drivers within each category are explained.

It is necessary to differentiate between natural hazards and disasters. Hazards are just the underlying natural processes that built the potential for harm but it needs a subject to experience the threat to become a disaster. As the focus is on supply chains the subject of the question here is the supply chain, which experience the impact of a natural catastrophe. The different types of natural disasters and their sub-types, as well as an explanation on each can be found in **Chapter 3**.

The impacts that natural threats can have on a supply chain and their performance are shown in **Chapter 4**. Beside the two major components where a supply chain is susceptible to natural disasters are explained and a literature review on currently used supply chain risks and country risk assessment approaches is conducted.

Based on the distinction between location and transport when it comes to supply chain vulnerability **Chapter 5** presents the concept of vulnerability of places in the context of this work. A literature review on vulnerability characteristics is conducted to identify explaining indicators for different levels of susceptibilities in different regions.

Chapter 6 explains the necessary steps for the impact assessment method *SCperformND*, starting with a general description, followed by a mathematical foundation.

In **Chapter 7** the method *SCperformND* is demonstrated within a case study. Starting with the identification of vulnerability indicators with the greatest influence on performance, followed by a detailed analysis on country basis.

Finally **Chapter 8** concludes with a summary of this work, as well as a critical appraisal and outlook for future research.

2 Supply chain vulnerability

2.1 Risk, vulnerability and related definitions

There are numerous definitions of ’risk’ existing, as well as with special focus on supply chains or disasters. To get a deeper understanding of the necessary background, definitions for the relevant terms are given, which shall apply for the rest of this work.

One possible reason for the high amount of differing definitions can be seen in the change of related contexts. That is for example the individual perception of risks changes over time, risks which have been perceived as relevant in history might have nowadays no or different meanings. Besides this, new risks came into place, for example from the use of state of the art IT-technology ([311], p.15, this paragraph is extracted from the authors Diploma-thesis p. 4).

Generally, **risk** can be defined as ’the probability of events that result in loss’ ([134], p.120), ’danger, damage, [...], injury or any other undesired consequences’ ([129], p.52). This definition concludes with the differentiation of risks regarding their probability of occurrence and their possible impacts. As can be seen in figure 2.1 are natural disasters located in the upper left quadrant and are therewith low probability, but high impact risks (to a supply chain). Given the apparently low probability of external risks, those risks are likely to be underestimated or are not in the focus of (supply chain) risk management. ’Most companies develop plans [just] to protect against recurrent, low-impact risks [...], but ignore high-impact, low-likelihood risks’([55], p.54). Nevertheless can external risks ’have [...] severe impact[s] in terms of magnitude in the area of their occurrence’ ([373], p.305) as well as cascading effects along the supply chain ([58], p.11f; [160], p.13) - even so the majority of those risks are predominantly exceptional ([313], p.244). That is why an effective (supply chain) risk management must investigate not solely internal risks, but also external risks. This is more than important as ’many of the threats to business continuity lie outside the focal firm’ ([58], p.6).

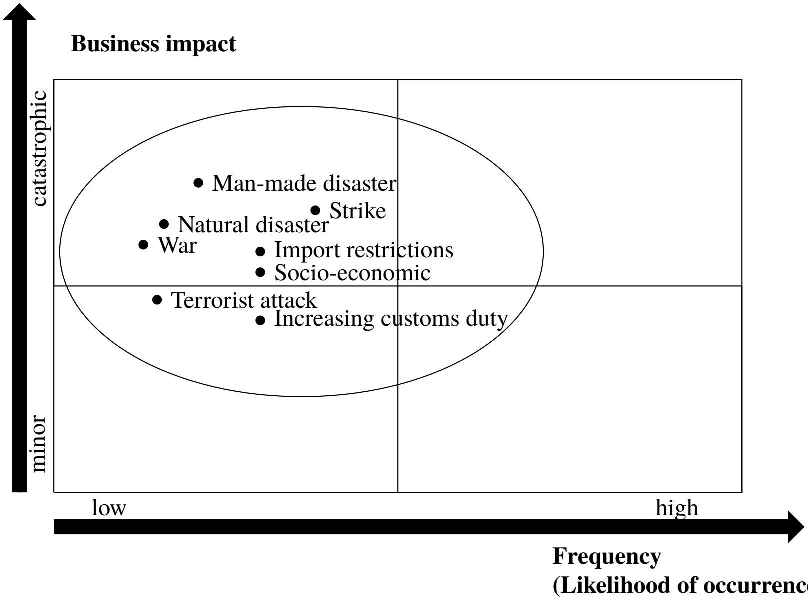


Figure 2.1: Risk map external events (sources: [313], p.244ff; [187], p.109; [206], p.172; [238], p.44)

In addition, the term ’risk’ must be seen in the specific field of investigation, in this work supply chains and natural disasters. Following the previous definitions are **supply chain risks** ’disruptions and disturbances of flows within the goods [...] networks [...], which have negative impacts on the objectives of single corporations respectively the whole supply chain regarding final customer benefits, costs, quality, time or value increases.’ ([168], p.42)[2]. Those negative outcomes are summarized under **performance impacts**. The sources of those disruptive triggers can lie in organizational, supply chain or environmental characteristics ([203], p.535). Therewith is ’any disruption at any stage in a supply chain that can be linked to environmental causes [...] ascribable to external risks’([63], p.2). Since natural disasters occur outside the supply chain network, those risks are part of the category of external (supply

[2]Of course disruptions in the information flow can also occur, but as this is not the focus of investigation, it is just focused on the flow of goods.

chain) risks, as already mentioned. So are disruptions which can be associated with organizational characteristics assigned to internal risks of the corporation itself, while supply chain characteristics describe internal risks caused by the characteristics of the supply chain network (so called network risks). Further details on supply chain risk classifications can be found in chapter 2.3.

Supply chain vulnerability can consequently be defined as 'exposure to serious disturbances [or disruptions], arising from risks within the supply chain as well as risks external to the supply chain' ([58], p.3).

As this work focuses on impacts of natural disasters on supply chain performances, it is inevitable to provide also a definition of risk in the context of disaster management. From this understanding the interaction of a hazard (man-made or natural) and a vulnerable condition results in risk ([332], p.6). A vulnerable condition or **vulnerability** are the 'pre-event, [...] characteristics or qualities of [...] systems that create the potential for harm' ([70], p.599). 'System: [is thereby] the system of analysis, such as a coupled human-environment system, a population group, an economic sector, a geographical region, or a natural system' ([111], p.157). In the given case, the system is the supply chain network itself, as well as the related points (e.g. countries) the supply chain network is linked to. Here characteristics of the location and the supply chain, that define the potential impact, must be considered. The factors, explaining differences in supply chain vulnerability between distinct locations, are investigated in greater detail in chapter 5.2.

Generally speaking vulnerability depends deeply on topic, field of investigation and research question ([36], p.152f; [140], p.199). That is why the chosen explanation is just applicable for this specific context, and is subject to change for other research questions.

A counterpart to vulnerability, is **resilience**: 'the ability of a supply chain [or other systems] to overcome vulnerability' ([134], p.125) and 'return to its original state or move to a new, more desirable state after being disturbed' ([58], p.2). The capability of a system, person or community to reach those states is described as **recovery** ([89], p.4). Details on recovery can be found in chapter 4.3. Additionally it is also necessary to take the different types of disasters into consideration, as the vulnerability to different types can vary ([36], p.152f; [217], p.1149). A description on different types of natural disasters is therefore given in chapter 3.2.

Based on the given definitions are the reasons for increased supply chain vulnerability presented in the following chapter.

2.2 Reasons for increased supply chain vulnerability

As stated in the previous chapter, supply chain risks can occur out of organizational, supply chain related or environmental causes. This three categories are the main factors explaining the increase in supply chain vulnerability, as can be seen in figure 2.2. All results presented here are findings of an intensive literature review, its results and sources can be seen in appendix A.1.

Organizational factors	Network factors	External factors
• Single sourcing • Outsourcing • Concentration on core competences • Changes in business strategy • Changes in business model • Focus on efficiency rather than effectiveness • Decreased capacities • Decreased vertical integration • Reduced inventory • More lean and agile operations • Just-in-time initiatives	• Increased interconnectedness and interdependence • Globalization • Increased competition • More sales channels / markets • Increased complexity	• Climate change • Increase in frequency and intensity of extreme weather events, catastrophes, disasters, natural hazards • Increased number of man-made hazards • Infrastructure break-down • Limited availability of scarce resources • Risk of epidemics • Cultural differences

Figure 2.2: Reasons for increased supply chain vulnerability (sources see appendix A.1)

To start with the smallest entity, the corporation itself, reasons for ascending supply chain vulnerability lie in organizational aspects. Often cost reduction initiatives or attempts at being competitive in an increasingly globalized market are the reasons for research. As those investments in competitiveness can be valuable in the short-run, severe risk increases can hit in the long-term, mostly only recognized when the first major disaster strikes. Centralization is also an important aspect, as companies focus on a few distribution and production locations only and therewith often reduce the supplier base and their inventories ([221], p.35). This is very useful when costs are taken into consideration solely, but can be a very risky approach when unforeseen events disrupt normal processes and business continuity. Other initiatives are lean and just-in-time strategies, which must be weighed against probable higher risks.

The next category, the **network factors**, occur outside of interactions of several corporations within the supply chain network and are thereby defined through the charactersitics of the supply chain network. Reasons for increased supply chain vulnerability are, beside others, emerging globalization strategies, resulting in outsourcing to low cost countries or in general more international procurement processes ([221], p.35). That means a disaster somewhere in the world can have devastating impacts all over the connected points, not just for supply chains but also for people and societies ([333] p.5, [148], p.192). This is also valid for domestic supply chains, but the impacts increase with the expansion of a network ([148], p.198).

External factors affect the network from outside and are beyond the influence of the members of the network. Often stated factors are disasters or the expected increase in intensity and frequency of weather events ([182], p.6, 237; [207], p.7; [373], p.301; [192]; [58], p.1ff; [57], p.189). The analyzed natural disaster are thus part of this last class.

2.3 Classification of supply chain risks

2.3.1 - in general

As well as for the definition of risk, numerous approaches to classify risks exist. Among others Pfohl 2002 ([220]), Hotwagner 2008 ([145]) and Lasch et.al. 2002 ([174]) distinguish between the following risk types in table 2.1.

Table 2.1: Classification of supply chain risks ([220], p.10ff; [145], p.24 and [174], p.113f)

Classification	Risk types
Deviation from expected results	pure risks / speculative risks
Level of risk	very small risks / small risks / medium risks / huge risks / life threatening risks
Point of origin	supply chain internal risks / supply chain external risks
Functional areas	R&D / Procurements / Logistics / Production / Sales / Finance
Insurability	insurable risks / non-insurable risks
Measurability	easy measurable / hardly measurable / very hard or not measurable
Scope	single risks / overall risks
Decision level	operative risks / tactical risks / strategic risks
Factors of production	labor risks / material risks / capital risks / resource risks

As stated in chapter 2.1 the following definition of supply chain risk shall apply: which are ’disruptions and disturbances of flows within the goods [...] networks [...], which have negative impacts on the objectives of single corporations respectively the whole supply chain regarding final customer benefits, costs, quality, time or value increases.’ ([168], p.42). According to the classification of supply chain risks these risks are pure risks, as they are ’just’ referring to a negative **deviation from the expected result** ([397], p.60). Speculative risks are not considered explicitly here, as they are not the focus of this work. Nevertheless it is necessary to be aware that there are also speculative risks and therewith not just a negative impact of risks, but also a ’chance’ to reach a better state after the occurrence of a risk or hazard (or more general: to gain a positive deviation from the expected result) ([220], p.11). Concerning the **level of risk**, risks can be graded from very small risks up to risks that threaten the livelihood of people or their existence. Within this category of life and existence threatening events can also natural hazards be summarized, as natural hazards are ’natural processes, which can lead to loss of human lives, injuries or other health related impairments, damages to property, loss of livelihood, and several services as well as to disturbances to the social and economic conditions of a society'([166], p.188). It can therefore be assumed that natural hazards are more likely huge risks than small or medium sized risks (or one of the other gradations), since they are 'normally accompanied by grave consequences' ([313], p.244). Regarding the **point of origin**, there are supply chain internal risks and supply chain external risks to be observed. Whereas supply chain internal risks are the result from processes of interaction between corporations within the supply chain network, external supply chain risks are the result of the interaction of the supply chain with its environment ([294], p.275; [157], p.201). These external or environmental risks are caused by events outside the influence of the supply chain, or events that can just barely be influenced ([399], p.28; [313],p.244). Internal supply chain risks can be subdivided in risks within the organizational boundaries of a firm (risks within the functional areas), and network-related or cooperation risks ([313], p.244; [294], p.275). As mentioned before network-related risks are the result of interactions between corporations within the supply chain. As already stated one of the reasons for the lack of attention on environmental risks, they are regarded as less likely than internal supply chain risks ([313], p.244). Nevertheless, external risks can 'have [. . .] severe impact[s] in terms of magnitude in the area of their occurrence' ([373], p.305) as well as cascading effects along the supply chain ([58], p.11f; [160], p.13). That means external supply chain risks and therewith natural hazards have a lower probability of occurrence than internal risks, but can have a much higher impact ([206], p.173; [238], p.44). Dependent on the size of a corporation and other related factors (e.g. industrial sector) a corporation has several **functional areas**, which can cause risk. It is worth mentioning that not necessarily a corporation has all above mentioned areas, but it can have more as well (dependent on the aforementioned influencing factors). **Insurability** is dependent on whether it is possible to identify and quantify (or at least estimate) the probability of occurrence of an event and its impact, and for the insurance company in addition the ability to set premiums ([171], p.15). To ensure the existence of a corporation it is useful to insure at least existence-threatening risks ([233], p.13f), like natural hazards. The problem is that meanwhile some insurers feel that natural hazards are uninsurable due to huge losses they have faced in recent years ([171], p.40). The **measurability** of risks is closely linked to their insurability as a prerequisite of measurability and therefore for the quantification of risks is the availability of data. Hence risks with a higher probability of occurrence are easier to quantify than risks with low occurrences ([233], p.9). The availability of (historical) data is essential to analyze the frequency and magnitude of natural hazards as well as their possible occurrence ([118], XV). Through their **scope**, risks can also be differentiated in single risks and the so called overall risk. Whereas a single risk is the result of a single decision or a chosen alternative, the aggregation of all single risks is the overall risk ([310], p.14f; [220], p.12). But it has to be considered that through interdependencies the sum of all single risks is not necessarily equal to the overall risk ([177], p.338 [145], p.24) The **decision level** differs between operative, tactical and strategic risks. Strategic risks influence the achievement of long-term goals (e.g. securing the existence of a corporation) and have an effect on the whole corporation or supply chain ([220], p.12; [172], p.532; [174], p.114). Operative and tactical risks affect short and mid-term goals and also 'just' a part of a corporation or supply chain ([113], p.35; [397], p.61; [220], p.13; [120], p.38). Concerning the **factors of production** labor, material, capital and resource risks can exist ([120], p.37). Depending on whether and to what extent these factors are used.

To summarize, natural disasters are pure risks with often life threatening impacts that affect the supply chain from externally (external risks). While insurability is hardly achieved, insurers had to face severe losses in recent years. Due to historical data records natural disasters are more easily measurable than other risks.

Beside the above mentioned types of risks, other classifications exist as well. Moreover is the systematization and relevance of risks dependent on factors like company size, industrial sector and others ([388], p.21). The given overview is an excerpt of the most relevant approaches in the context of supply chain risk management and introduces the classification of supply chain risks regarding environmental risks in the next chapter.

2.3.2 - in accordance to external risks and hazards

Regarding the topic of this work, to assess the impacts of natural disasters on supply chains it is necessary to provide a detailed overview of existing classification approaches that take those risks into consideration. In table 2.2 such an overview is provided. The classifications used are separated by slashes and those related to external risk are marked bold. Even though it is just a sample it shows that the majority of authors refer to internal versus external supply chain risks, but often under different names and descriptions.

The hierarchical degradation of supply chain risks and their explanation can be found in figure 2.3 to 2.5 and in the text below.

Table 2.2: Classification of supply chain risks in accordance to external risks

Classification	Source
(Supply chain) internal risk sources / **(Supply chain) external risk sources**	[135], p.502ff [159], p.112 [313], p.244 [294], p.275f [298], p.60ff
Physical / Financial / Informational / Relational / Innovational	[49], p.384f
Risks - with source inside the corporation (organizational risks)/ Risks - outside the corporation, but internal to the supply chain (network risks) / **Risks - outside the supply chain (within the environment)**	[141], p.116f [58], p.4ff [187], p.100ff [157], p.201f [156], p.114
Supply-chain-internal risks (supply risk) / **Supply-chain-external risks, related to specific procurement markets (environmental risks) / Supply-chain-external risks, not related to specific procurement markets (external environmental risks)**	[168], p.68ff
Supply Risk / Demand Risk / Process risk / Control Risk / Environmental Risk	[57], p.194 [56], p.238
Supply risk / Process risk / Demand risk / **Corporate-level risks**	[245], p.22
Supply risks / Operational risks / Demand risks / **Other risks**	[148], p.197ff
Supply risks / Process risks / Demand risks / Intellectual property risks / Behavioral risks / Political / Social risks	[300], p.13f
Environmental risk sources / Demand risk sources / Supply risk sources / Process risk sources / Control risk sources	[156], p.122f
Demand-side risk / Supply-side risk / **Catastrophic risk**	[373], p.304

Plan risk / Source risk / Make risk / Deliver risk / Return risk	[399], p.26ff
Network risks / Process risks / Product risks / Infrastructure risks	[371], p.87
Operational risks / **Disruption risks**	[299], p.453
Set-up risks (strategic, ex-ante) / Partnering risks (strategic, ex-post) / Initiation risks (operative, ex-ante) / Transaction risks (operative, ex-post)	[224], p.26
Strategic risk / Operations risk / Supply risk / Customer risk / Asset impairment risk / Competitive risk / Reputation risk / Financial risk / Fiscal risk / Regulatory risk / Legal risk	[129], p.53
Disruptions / Delays / Systems / Forecast / Intellectual property / Procurement / Receivables / Inventory / Capacity	[55], p.53ff
According to global circumstances (macro-environment) / According to task-specific circumstances (competitive environment)	[220], p.13ff
Enterprise risk: core business risk / **non-core business risk** Core business risk: value chain risk / operational risk; Non-core business risk: **event risk** / recurring risk (credit risk / tax risk / market risk) **Event risk:** legal / regulatory / political / hazard / economic / **natural** / reputation	[239], p.221ff
Environmental factors / Industry factors / Organizational factors / Problem-specific factors / Decision-maker related factors **Environment risk:** political uncertainty / Policy uncertainty / Macroeconomic uncertainty / social uncertainty / **natural uncertainty**	[227], p.101ff
Uncertainty between node enterprises / uncertainty in node enterprises / uncertainty of market demand / **uncertainty of external environment** **Environmental risk: natural environment risks** / social environment risks / economic risks	[390], p.2f
Customer risks / Supplier risks / Bureaucratic risks / Infrastructural risks / **Catastrophe risks**	[376], p.102

To start with internal supply chain risks, those risks can be divided in organizational and network risks ([187], p.100ff; [156], p.114; [58], p.4ff; [157], p.201f; [141], p.116f). Organizational risks are internal to the corporation and internal to the supply chain as well, so the source of risks lies within the boundaries of the corporation and can directly be influenced by the corporation ([313], p.244; [187], p.108). Under this category all risks are subsumed out of the functional areas, e.g. sales and procurement risks (see also chapter 2.3.1 for this classification). Processes and their control are then the connecting elements to other points within the supply chain network and that link their partners ([157], p.201f; [204], p.437). The source of risks for network risks lies outside the corporation but within the supply chain ([187], p.108). The upper part of figure 2.3 illustrates this classification, while the lower box explains organizational risks (which are internal to the supply chain and to the corporation).

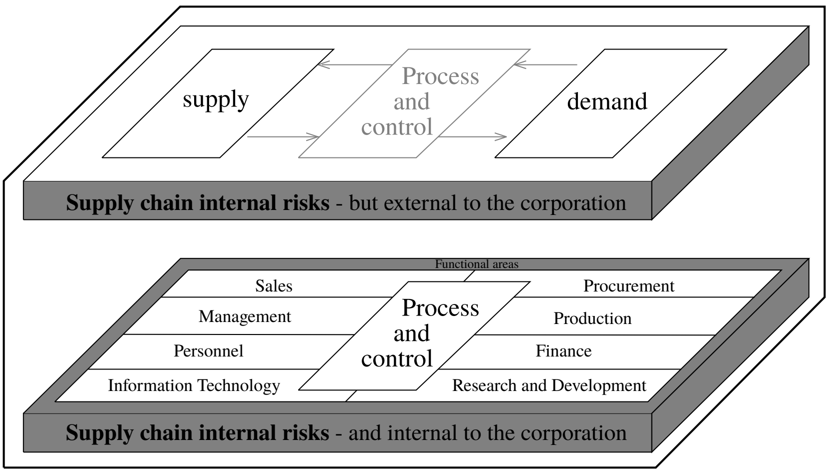


Figure 2.3: Internal supply chain risks (based on [168])

On the other hand external risks occur, which are caused by sources outside the supply chain, but within the environment of that system, that have direct or indirect impact on the network ([141], p.116f; [298], p.60ff). That means environmental supply chain risks are 'risks beyond the influence of the members of the entire supply chain' ([187], p.108). However the effect of those external supply chain risks is not limited to the supply chain only; they can even affect the market places themselves ([58], p.4ff). That is why it is necessary to distinguish external supply chain risks further into supply chain risks related to specific procurement markets and supply chain risks not related to specific procurement markets ([168], p.68ff). Examples of risks that are related to the procurement markets are: social, political, cultural, legal, economic, technological and ecological risks ([168], p.68ff; [220], p.13ff; [58], p.4ff, [156], p.122f; [294], p.275f; [90], p.5), which can also be seen in figure 2.4. Supply chain external risks related to specific procurement markets are therewith 'the result of characteristics and circumstances of the global procurement market' whereby supply chain risks not related to specific markets 'cannot be assigned to a specific country' ([168], p.68ff) or market, even if they occur in specific countries or regions. In this category natural disasters can be classified, which is explained in detail later.

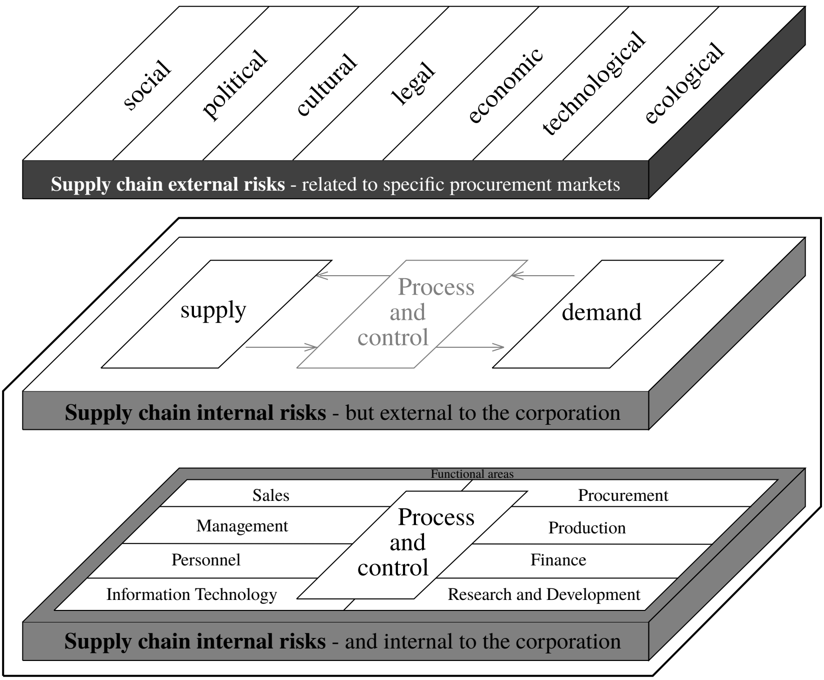


Figure 2.4: External supply chain risks (based on [168])

The different characteristics of the procurement market that build the potential for harm to a supply chain are the third layer in figure 2.4. Whereby the legal risk of a procurement market is determined by the legal circumstances in the sourcing country, through its legal and economic system ([168], p.71). To this category belong e.g. environmental legislation, tax law and the ability of a country to protect intellectual property (or more general: a lack of legal protection) ([220], p.15; [55], p.57; [386], p.11). The legal risk is linked to the economic system of a country and vise versa. The economic risk describes all 'macroeconomic influences within a spatially delimited area' ([130], p.17). Which are, among others, for a specific procurement market: exchange rates, economy, inflation, foreign trade, interest rates and infrastructure ([386], p.11; [241], p.305). This category entails also financial risks, which 'expose [...] a firm to potential loss through changes in financial markets' ([129], p.53). 'Unpredictable changes in political structures or ideologies' ([168], p.70) are seen as the political risk of the supply chain environment. Caused by a high degree of uncertainty it is very difficult to act in a proactive manner when it comes to political risks ([220], p.15). Single risks in this category are: expropriation, trading restrictions, white collar crime, terrorism (man-made hazards) and political (in)stability ([386], p.11; [397], p.71; [168], p.70f; [374], p.66; [241], p.305). Social and / or cultural risks reflect the 'values, norms, attitudes and beliefs of the social units within a country' ([168], p.72). They are not just occurring because of differences in the aforementioned categories, but could also be the result of 'inadequate knowledge about people, culture, and language' ([148], p.200). Social aspects or moreover demographics, the distribution of income and wealth and the quality of education ([386], p.11; [130], p.69; [398], p.12). Attributes of the technological environment are the information and communication technology, knowledge transfer, process and product innovations, as well as the technology for material flows ([386], p.11; [130],p.68; [168], p.72). The technological risk is therefore the state of the technological development within the respective country ([168], p.72). The last category of environmental supply chain risks with a relation to specific procurement markets are ecological risks, which are for example determined by environmental protection, ecological damage and recycling ([386], p.11) as well as 'the geographical location of suppliers or the availability of raw material' ([6], p.66). As mentioned before also external risks exist that are not related to specific procurement markets and cannot be assigned to a particular country or region. This category entails natural and man-made hazards (e.g.

terrorism, acts of war). As the focus of this work is the investigation and assessment of natural threats, man-made hazards are not considered any further. Work on man-made hazards can for example be found in [60].

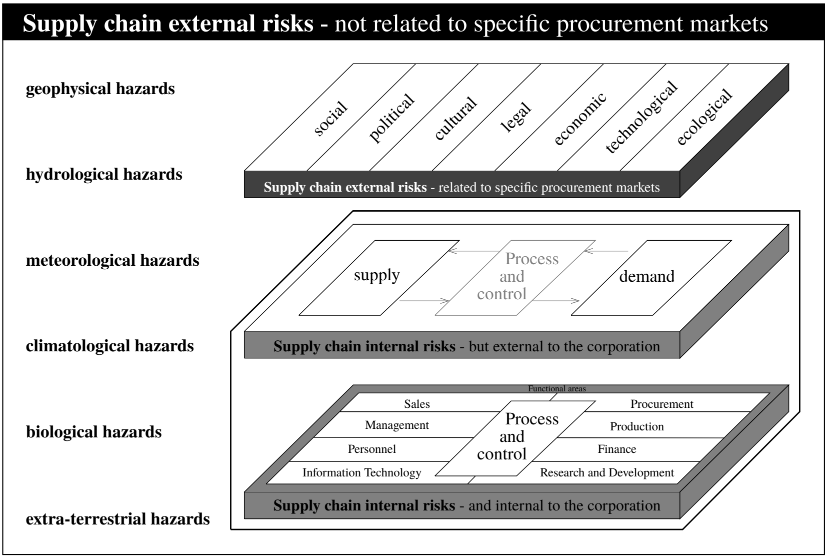


Figure 2.5: External supply chain risks - not related to specific procurement markets (based on [168])

Natural hazards can be defined as: 'natural processes, which can lead to loss of human lives, injuries or other health related impairments, damages of property, loss of livelihood, and several services, as well as to disturbances to social and economic conditions of a society' ([166], p.188) - and so to disruptions or disturbances of a supply chain. As this definition of natural hazards can result in all these negative outcomes, it needs a system or asset to be affected to become a disaster. Details on that differentiation can be found in chapter 3.1. Subcategories of natural hazards are meteorological hazards, hydrological hazards, geological hazards, climatological hazards, extra-terrestrial hazards and biological hazards ([166], p.188f; [86], p.1035).

It is again worth to mentioning that supply chain risks can be classified in various manners, which sometimes also overlap. The developed approach in this work fits the topic best, as it presents a distinction between external supply chain risks that are related to specific procurement markets and those risks which cannot be associated with a specific market or region.

To understand the differences between different disaster types the next chapter gives an explanation on the distinction between hazards and disasters, followed by an overview on the disaster types and their related subtypes.

3 Natural hazards and disasters

3.1 Difference between hazards and disasters

As already stated natural hazards are 'natural processes, which can lead to loss of human lives, injuries or other health related impairments, damages of property, loss of livelihood, and several services, as well as to disturbances to social and economic conditions of a society' ([166], p.188). But for a hazard to become a disaster 'there has to be a subject to experience the hazard or the threat. For example, people, infrastructure and economic activities' ([333], p.30). In the following case the supply chain, respectively the location of a supplier or own production facilities are the affected subjects. So while there is a risk of being affected by natural processes, they do not necessarily result in a disaster. The more assets (subjects) at risk the higher the potential (perceived) impact of a disaster. Moreover the disaster type has an effect on the extent of damage, e.g. explained through a different speed of onset. While earthquakes, tornadoes and hurricanes have sudden onsets, drought realizes slowly ([380], p.476). Other differentiating factors are the duration of impact and the length of forewarning. An outline on differentiating factors can be found in table 3.1.

Table 3.1: Classification of disasters by duration and length of forewarning ([4], p.10)

Type	**Duration**	**Length of forewarning (if any)**
Lightning	instant	seconds-hours
Avalanche	seconds-minutes	seconds-hours
Earthquake	seconds-minutes	minutes-years
Tornado	seconds-hours	minutes
Landslide	seconds-decades	seconds-years
Intense rainstorm	minutes	seconds-hours
Hail	minutes	minutes-hours

Tsunami	minutes-hours	minutes-hours
Flood	minutes-days	minutes-days
Subsidence	minutes-decades	seconds-years
Windstorm	hours	hours
Frost or ice storm	hours	hours
Hurricane	hours	hours
Snowstorm	hours	hours
Environmental fire	hours-days	seconds-days
Insect infestation	hours-days	seconds-days
Fog	hours-days	minutes-hours
Volcanic eruption	hours-years	minutes-weeks
Coastal erosion	hours-years	hours-decades
Accelerated erosion	hours-millennia	-
Drought	days-months	days-weeks
Crop blight	weeks-months	days-months
Expansive soil	months-years	months-years
Desertification	years-decades	months-years

The next chapter will explain the different types of natural disaster as well as their classification.

3.2 Types of natural disasters

In this chapter an overview on different types of natural disaster is given, which can be classified according to figure 3.1. The types of classification are geophysical, hydrological, meteorological, climatological, extra-terrestrial and biological events.

Whereas natural hazard describes just the possible occurrence of a natural process, as explained in the previous sub chapter, 'it becomes a natural disaster if people or values are influenced negatively' ([86], p.1120). A disaster is therewith 'a situation or event which overwhelms local capacity, necessitating

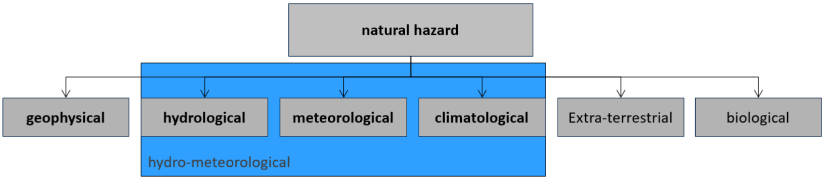


Figure 3.1: Types of natural disasters

a request to a national or international level for assistance' ([236], p.2). A negative consequence is assumed on supply chain performance, it is hereafter referred to as disaster.

To investigate the possible occurrence of natural threats for a certain region (and the effects of natural disasters on supply chains) it is necessary to analyze historical disaster data for each disaster type. Historical data in this work is derived from *The Dartmouth Flood Observatory* for floods. There are large floods listed that caused 'significant damage to structures or agriculture, long (decades) reported intervals since the last similar event, and/or fatalities' for all regions worldwide ([74]). Hurricanes as well as earthquakes within the United States of America are sourced from *The U.S. Department of Homeland Security* ([101]), where the data is extracted from the disaster declarations. And earthquake data for New Zealand stems from GeoNet (Geological hazard information for New Zealand [117]). The frequency analysis to it can be found in chapter 6.1. Cyclones (as found for example in Australia) are here subsumed 'under' flood, as the major impact was felt through the massive flooding after the cyclone. Other disaster types are not considered, as no studies could be found in the literature, where data on businesses or supply chains after a disaster where analyzed. Details on that are shown in chapter 6.

A database for all disaster types on a global scale can for example be found at *EM-DAT: The Emergency Events Database* ([76]). Beside this often country specific data bases exist, if a special focus is needed. Examples here are the *Austrian Research Center for Forests* ([17]) for Austria or the *Instituto de Estudios Ambientales (IDEA) (Universidad Nacional de Colombia)* for Colombia ([99]).

For the analysis it should also be remembered that external supply chain risks, not related to a specific procurement market (see chapter 2.3.2), cannot be associated with a specific country. Nevertheless natural disasters and their possible negative effects are mostly reported on country level ([236], p.3).

That is why the vulnerability of places approach is used (introduced in chapter 5), in order to get a more detailed picture of the regions of interest, meaning, that while starting with the country perspective, information is attempted to be broken down to a smaller focus area (the place or region).

In the following sub chapters single types of natural disasters are shortly described. A profound definition of all types and sub-types can be found in appendix A.7.

3.2.1 Hydrological disasters

Hydrological disaster are caused by the occurrence, movement, and distribution of surface and subsurface water ([166], p.188) and are divided in floods, landslides and wave actions with their related sub-types, which can be seen in table 3.2.

The first entry '**floods** [describe] [...] an overflow or inundation that comes from a river or other body of water and often threatens lives and properties' ([143], p.64). While **coastal floods** are 'higher-than normal water levels along the coast caused by tidal changes or thunderstorms that result in flooding, which can last from days to weeks', are **riverine floods** 'a type of flooding resulting from the overflow of water from a stream or river channel onto normally dry land in the floodplain adjent to the channel' (here and following [152], p.13ff). As the name implies, **ice jam floods** are 'the accumulation of floating ice restricting or blocking a river's flow and drainage. Ice jams tend to develop near bends and obstructions (e.g.,bridges)'. And **flash floods** are 'heavy or excessive rainfall in a short period of time that produce immediate runoff. Creating flooding conditions within minutes or a few hours during or after the rainfall'([152], p.13f).

More than two thirds of all reported disasters and one third of all damages can be associated with flooding, making it one of the most frequent natural disasters (beside storms) ([194]). This aspect is also illustrated in figure 3.2. Even within literature, sources dealing with supply chains or businesses in the aftermath of natural disasters in chapter 6, where more sources identified dealing with flooding than any other disaster type. This fact is aggravated as 'hydrometeorological hazard frequencies and magnitudes might also change in the near future due to climate change and/or environmental degradation' ([217], p.1159). That is why flooding is a key aspect of investigation in the following chapters.

Table 3.2: Hydrological disasters ([77])

Disaster main type	**Disaster sub-type**
Flood	Coastal flood Riverine flood Flash flood Ice jam flood
Landslide	Avalanche (snow, debris, mudflow, rockfall)
Wave action	Rogue wave Seiche

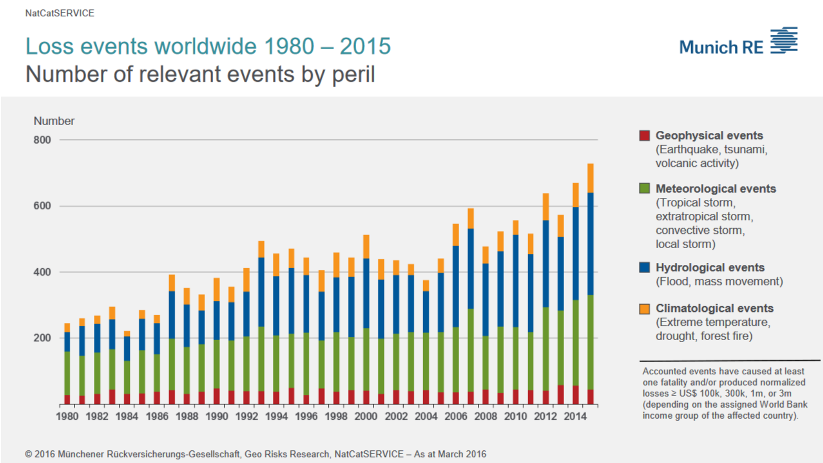


Figure 3.2: Loss events worldwide [196]

Landslides, 'include [...] many downslope movements of soil, rock, or other Earth materials. Landslides can be activated by earthquakes, rapid snowmelt, intense rainstorms, groundwater rise, slope toe cutting by rivers, or volcanic eruptions, in conjunction with gravity and occur when driving forces, such as gravity, exceed the frictional strength of the slope materials' ([228], p.435). And **wave actions** can be defined as 'wind-generated surface waves that can occur on the surface of any open body of water such as oceans, rivers and lakes, etc.' ([152]). For those two types no literature sources could be identified referring to businesses or supply chains and they are therewith not part of the impact assessment. But for reasons of completeness these types are described as well, what is valid for all following, not included disaster types.

3.2.2 Meteorological disasters

Meteorological disaster are caused by short-lived, extreme weather and atmospheric conditions ([166], p.188). Types of meteorological disaster are storms and extreme temperature with their related sub-types, which can be found in table 3.3.

Table 3.3: Meteorological disasters ([77])

Disaster main type	Disaster sub-type	Disaster sub-sub-type
Storm	Extra-tropical storm Tropical storm	
	Convective storm	Derecho Hail Lightning / Thunderstorm Rain Tornado Sand / Dust storm Winter storm / Blizzard Storm / Surge Wind
Extreme temperature	Cold wave Heat wave	

	Severe winter conditions Fog	Snow / Ice Frost / Freeze

High wind speeds can have severe impacts on (critical) infrastructure, properties, humans and therewith also on supplier or production facilities within a supply chain network. Damage to constructions starts when the wind speed exceeds 72,4 km/h ([228], p.440). The terminology for tropical cyclones varies regionally, so this is just one possible way to describe this disaster types. A **tropical cyclone** is 'an organized, cyclonically rotating system of convection driven by fluxes of heat derived from the ocean'. While **Tropical storms** are 'tropical cyclones that have maximum sustained winds between 17 and 32 m/s (34-63 kts); intense tropical cyclones – those with winds of at least 33 m/s (64 kts) - are called hurricanes in the Atlantic and eastern North Pacific basins and typhoons in the western North Pacific' ([169], p.481). The impact assessment in chapter 6 also incorporates several hurricanes that affected the United States of America, while typhoons could not be identified in the literature research. An **extra tropical storm** is 'a type of low-pressure cyclonic system in the middle and high latitudes (also called mid-latitude cyclone) that primarily gets its energy from the horizontal temperature contrasts (fronts) in the atmosphere' ([152]). And **extreme temperature** is 'a general term for temperature variations above (extreme heat) or below (extreme cold) normal conditions' ([152]).

3.2.3 Climatological disasters

Climatological disasters are caused by long-lived atmospheric processes (climate variability) ([166], p.188). Types of disaster here are drought, glacial lake outburst and wildfire as can be seen in table 3.4.

Table 3.4: Climatological disasters ([77])

Disaster main type	Disaster sub-type
Drought	
Glacial lake outburst	

Wildfire	Forest fire Land fire: brush, bush, pasture

Drought is ’an extended period of unusually low precipitation that produces a shortage of water for people, animals and plants’ ([152]). ’**Glacial lake outburst** floods (GLOFs), also known as jokulhlaups, occur when there is a sudden release of water from beneath or behind a glacier’ ([125], p. 398). A **wildfire** is ’any fire occurring in vegetation areas regardless of ignition sources, damages or benefits’ ([332], p.7). For all three types no evidence in the literature research was found that underpins an impact of those types on supply chain performance. So these three types are not part of the analyzes, even though possible impacts are obvious, especially for crops (food supply chains) when a drought or wildfire takes place. The focus of this work lies within industrial supply chains.

3.2.4 Geophysical disasters

Geophysical disasters (sometimes also declared as geological disasters) are events that originate from solid earth ([166], p.187) and ’may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation’ ([332], p.4). Subtypes are earthquakes, mass movements and volcanic activities (see table 3.5).

Table 3.5: Geophysical disasters ([77])

Disaster main type	**Disaster sub-type**
Earthquake	Ground shaking Tsunami
Mass movement	
Volcanic activity	Ash fall Lahar Pyroclastic flow Lawa flow

An **earthquake** is here defined as 'a tectonic or volcanic phenomenon that represents the movement of rock and generates shaking or trembling of the Earth' ([48], p.208). While **ground shaking** is a 'general term referring to the qualitative or quantitative aspects of movement of the Earth's surface from earthquakes or explosions. Ground motion is produced by waves that are generated by sudden slip on a fault or sudden pressure at the explosive source and travel through the Earth and along its surface' ([232], p.59). 'Ground shaking is the primary cause of earthquake damage to man-made structures. When the ground shakes strongly, buildings can be damaged or destroyed and their occupants may be injured or killed' ([343]). For the quantification of earthquakes the Richter Scale is applied, which allows to scale earthquakes by its size ([26], p.13). Richter (1935) describes the gradation as following: 'In general, shocks of magnitudes 0,1,2 are not reported as felt; shocks of magnitudes 3 and 4 are felt, but cause no damage; magnitude 5 may cause considerable minor damage; magnitude 6 is usually destructive over a limited area; and magnitude 7 and 8 transgress the lower limit of major earthquakes' ([230], p.14). Following this classification were historical earthquake data in chapter 6 considered from magnitude 6 on, as it needs at least a destruction to impact supply chains in a noticeable manner.

Mass movements are 'a variety of processes that result in the downward and outward movement of slope-forming materials composed of natural rocks, soil, artificial fill, or combinations of these materials' ([240], p.657). A **volcanic activity** is any 'volcanic event near an opening/vent in the Earth's surface including volcanic eruptions of lava, ash, hot vapour, gas, and pyroclastic material ([152]). One major volcanic event that strongly affected supply chains all over the world was the eruption of Eyjafjallajökull in 2010 (see [242]), as stated in the introduction.

3.2.5 Extra-terrestrial disasters

Extra-terrestrial disasters are caused by asteroids, meteoroids, comets, and by changes in interplanetary conditions ([152], [166], p.188). Types are impact and space weather as can be seen in table 3.6.

Table 3.6: Extra-terrestrial disasters ([77])

Disaster main type	Disaster sub-type
Impact	Airburst
Space weather	Energetic particals
	Geomagnetic storm

Impact is defined as ’a type of extraterrestrial hazard caused by the collision of the Earth with a meteoroid, asteroid or comet’ ([152]). ’**Space weather** is the chain of processes from eruptions on the sun, their passage through interplanetary space, and the interaction with the Earth’s magnetic field that leads to disturbances in the Earth’s magnetosphere, ionosphere, and on the ground that represent a hazard to man-made technology and human life’ ([30], p.937). As the focus of this work are supply chains without substantial literature that shows influences from extra-terrestrial disasters on supply chains, these types were excluded from further evaluations.

3.2.6 Biological disasters

Biological disasters are ’processes of organic origin or those conveyed by biological vectors, including exposure to pathogenic micro-organisms, toxins and bioactive substances, which may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation’ ([332], p.2). Main types are epidemics, insect infestation and animal accidents (see table 3.7). As the focus lies on industrial supply chains those disaster types are not investigated further, but stated for the purpose of completeness. Moreover it would be necessary to consider the biological processes behind the outbreak.

Epidemic is ’either an unusual increase in the number of cases of an infectious disease, which already exists in the region or population concerned; or the appearance of an infection previously absent from a region’ ([75]). Under **insect infestation** we understand ’the pervasive influx, swarming and/or hatching of insects affecting humans, animals, crops, and perishable goods. Examples are locusts and African Bees’ ([152], p.15).

Table 3.7: Biological disasters ([77])

Disaster main type	**Disaster sub-type**
Epidemic	Viral disease Bacterial disease Parasitic disease Fungal disease Prion disease
Insect infestation	Grasshoper Locust
Animal accident	

And **animal accidents** are encountering of humans ’with dangerous or exotic animals in both urban and rural environments’ ([152], p.12).

The impacts of the defined natural disasters on supply chains are described below.

4 Impacts of natural disasters on supply chains

As mentioned earlier external risks to a supply chain are often underestimated, as their occurrence is more or less rare while internal risks have often high occurrences. One reason for that might be, that 'firms may find it difficult to justify certain costly strategies for mitigating supply chain disruptions that rarely occur' ([375], p.122). Nevertheless the impacts of external risks can be much more devastating than other categories of risk.

The impact of natural disasters is regarded here from an economic perspective, where three categories in figure 4.1 can be distinguished.

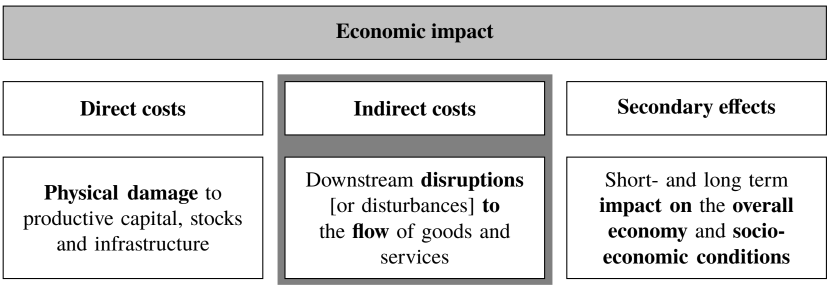


Figure 4.1: Economic impacts of disasters ([336], p.12)

Concerning supply chains effects are defined as indirect costs that lead to perturbations within the flow of goods. Services in this work are not considered explicitly, but can of course be affected as well. As stated, can those 'intangible and indirect effects may have an equal, if not greater, impact to an organisation's ability to operate than the direct damage to an organisation [...]' ([158], p.8). While under direct damage the immediate effects of a disaster are subsumed ([79], p.2). Those physical damages can include (but are not limited to) damage to or destruction of buildings, inventories and materials (here and following

[379], p.104). Also lifeline disruptions, like the disruption of water supply, electricity and telecommunications are possible, on which business operations are strongly dependent. 'For example, [can] firms [...] be forced to close down for extended periods of time if they lack critical power supplies or access to natural gas. Furthermore, businesses might lose suppliers or buyers as a result of power outages in impacted areas.' ([379], p.104). And business closure is moreover the most frequent consequence natural disasters have on business performance, which can be reread in chapter 6.1.

Most natural disasters can be devastating, when they hit a critical path within the network. Those are defined through single sourcing, long lead times and high levels of risk ([58], p.8), resulting e.g. in non availability of material and resources, cost increases or sales damages ([58], p.53). That is why those paths should be precisely monitored and first of all considered in the impact assessment of natural disasters on supply chains. For not yet established supplier relationships a general assessment of all potential suppliers (locations) is recommended. As it is even more difficult to assess indirect than direct damages ([136], p.159), e.g. due to their intangibility, a method to quantify or estimate those impacts must be identified or developed and at least applied. Therefore a literature review on current supply chain risk and country risk approaches with a focus on natural disasters was conducted, whose results are presented in chapter 4.4. Beside this, it is important to consider that 'regional economies behave differently when they face a disaster' ([136], p.151f), what is also valid for supply chains or supply chain networks. That is also why differences in regions (see chapter 5) have to be taken into account when the impacts of natural disaster on supply chains are evaluated.

Further are indirect impacts differentiated in disturbances and disruptions, which are explained in chapter 4.1.

4.1 Disturbances vs. disruptions

Disasters affect a supply chain in different ways, namely disruptions and disturbances, as can be seen in figure 4.2.

The major differences between disturbances and disruptions are their horizon of time as well as their extend of impact. While disturbances do not last for long periods (for example several hours) and have a limited extent (for

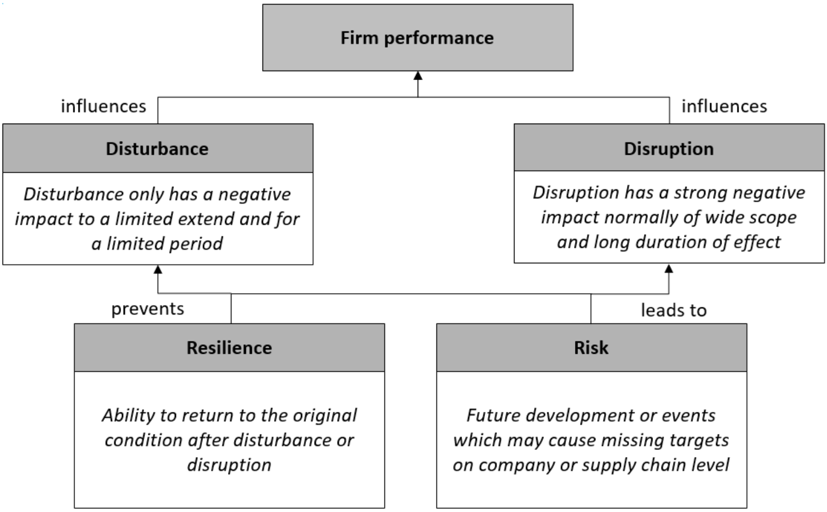


Figure 4.2: Disruption vs. disturbance (based on [221], p.35)

example just on one supplier), disruptions can have a long lasting influence on certain factors (affecting a supply chain for months up to years) within a wider extent (where several partners in the network could be affected). Disturbances can be possibly problems in quality, delivery defaults or demand fluctuation, which normally can be prevented through risk management measures. On the other hand result disruptions in severe effects, also on the financial situation of a corporation ([221], p.34; [238], p. 43; [55], p.55; [58], p.1). What can be 'significant supply-chain delays triggering stock-outs, inability to meet customer demand and increase in costs' ([22], p.4068), as well as the 'inability to produce goods' ([148], p.199). Due to carry-over effects can disruptions in the chain of one corporation also easily result in disturbances in the chain of another dependent corporation, even so the corporation is not affected itself ([316], p.225). Both, disturbances and disruptions, can therefore negatively influence a corporations' performance to certain extends ([22], p.4068; [55], p.54). Details on impacts of natural disaster on performances can be found in chapter 4.3. Here are natural disasters (external risks) the triggering event (in figure 4.2 defined as risk) leading to the aforementioned perturbations. As stated in chapter 2.3 risks can also occur inside the supply chain ([98], p.184), but this is not the focus so internal risks are excluded from further investigations.

As a supply chain is a dynamic conjunction it is inevitable that there are always disturbances and disruptions (from different sources), which cannot completely be eliminated. What is important to note is, that corporations know their supply chain (network) well, thus disturbances and disruptions can be detected early and negative effects can quickly be determined and measures are implemented ([22], p.4067). This so called agility (sometimes also referred as flexibility) is 'the ability to respond rapidly to unpredictable changes in demand or supply. Many organisations are at risk because their response times to demand changes or supply disruption are too long.' ([58], p.10).

To gain an overall insight of risk situations of a supply chain, it is necessary to not just investigate the triggering event, but also the susceptibility (determined through different characteristics) of a supply chain respectively location ([375], p.122). The susceptibility is referred to as supply chain vulnerability, which was already defined in chapter 2. An overview of supply chain characteristics that influence supply chain vulnerability is given in chapter 4.3.1, following chapter 4.2 where the aspects of transport and location susceptibility are explained.

As described in chapter 2.2 it is expected that the frequency and intensity of disrupting events, like natural disasters, is increasing. Hence corporations have to deal more often with supply chain disruptions ([22], p.4068). The more a supply chain is able to absorb those external shocks and re-organize back to a functioning system, the more resilient the supply chain is considered to be (see the lower left part of figure 4.2) ([70], p.599). So the direct damage happens at a point in time, the disruption lasts from the triggering event until the system has recovered ([234], p.5).

For the management of disruptive triggers the following steps should be taken into account (taken from [22], p.4069):

- **Disruption discovery**: to successfully recover (i.e. reduce or eliminate the negative impact) from a supply-chain disruption, the firm must have in place an effective means of discovering supply-chain disruptions.
- **Disruption recovery**: once the disruption is discovered, how does a firm effectively recover from a disruption?
- **Supply-chain redesign**: we seek insights into how the supply chain can be re-designed to become more resilient.

As a first step, the discovery is very obvious when a natural disaster strikes with a sudden onset. Non-detection is nearly impossible. Natural threats with a slow onset are not that obvious, but are normally detected as well - but of course dependent on the presence of any negative effects. The second step takes the implementation of measures to overcome the disruption into account, while the last target supply chain design improvements, reducing future possible negative impacts for a corporation respectively a supply chain. As the last step implies supply chain design is a vital part to effectively manage supply chain risks and to overcome supply chain vulnerability. That is why, aspects concerning the design of a supply chain must be considered from the first day on. Starting from supplier selection under consideration of all risk aspects (most of all including external risks), to effectively manage the existing supplier base and strengthen long-term relationships (just to state a view).

Following on below are the two major parts that can be affected - transport and location. The differences in their susceptibility are also explained.

4.2 Transport vs. location

Looking at a supply chain, it generally shows two major parts: locations and the transport of goods, which connect the different points within the network. Even though there are differences in the services to supply chains, the aspect of interconnectedness between the nods is still valid. Nevertheless here only industrial supply chains with flow of goods are considered.

It can be assumed that if a disaster strikes, before and after, it is mostly the location that is affected (see figure 4.3). The transport is consequently influenced through for example impossible supplies to and from a directly affected corporation or through interconnections also from and to dependent locations especially where the types of disaster are the aforementioned hydrological, meteorological, climatological and geophysical ones. But of course natural disasters can also impair the transport directly, but normally transport routes are checked in advance and firms change routes according to weather conditions. In contrast decisions on locations for production facilities or suppliers are generally more long-term oriented and cannot be changed permanently. Thus decisions on supply chain design should be made very carefully (as already stated in the previous chapter). Given all that, the location in this work is the primary field of investigation. This leads to the concept of vulnerability of places, which is explained in chapter 5.

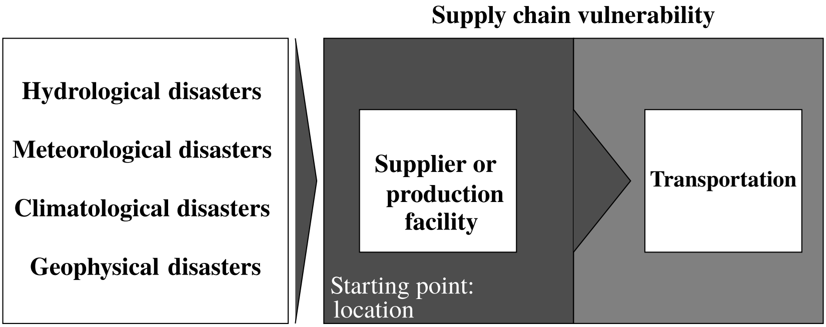


Figure 4.3: Supply chain vulnerability - transport vs. location

Details about the impacts of natural disaster on supply chain performance are now shown in chapter 4.3.

4.3 Performance impact and recovery

As explained earlier the effects that disasters can have on a supply chain are distinguished in disruptions and disturbances, while natural disasters more often result in disruptions. And 'any serious disruption will affect the performance of a company in predictable ways', which can be 'measured by sales, production level, profits, customer service or another relevant metric' ([238], p.42). 'Supply Chain Performance refers [therewith] to the extended supply chain's activities in meeting end-customer requirements, including product availability, on-time delivery, and all the necessary inventory and capacity in the supply chain to deliver that performance in a responsive manner.' ([131], p.61). While 'the full impact of some disruptions is felt immediately. [...] Other disruptions can take time to affect a company, depending on factors such as the magnitude of the disruption, the available redundancy, and the inherent resilience of the organization and its supply chain' ([238], p.42). Those factors are defined in the following chapter 4.3.1.

4.3.1 Supply chain characteristics that influence disaster impact and recovery

’Recovery is a measure of recovery from the disaster’, e.g. measured as ’the number of days that passed before resuming production’ ([316], p.219) and is influenced by different supply chain and business characteristics, as well as vulnerability factors within a region (for the factors of place vulnerability see chapter 5.2.2). From the supply chain perspective the structure of the network and the parties involved are major aspects of influence on supply chain vulnerability ([375], p. 123). For definitions on supply chain vulnerability see chapter 2.

Influencing aspects are **supplier characteristics**, as well as the **supplier base** ([375], p.123), with their individualising factors. Those relationships reveal the risk of **dependence**, e.g. ’when firms depend on processed materials, parts, or components from suppliers affected by a disaster, these downstream firms may have to shut down their operations even when they themselves are unaffected by the disaster’ ([316], p.218). Todo et al. (2015) ’hypothesize [therefore] that a firm’s recovery from a disaster becomes more difficult with an increasing **number of connections** with suppliers and clients within the impacted area’. This is also valid for connections to indirectly associated corporations, as the likelihood to be connected with an affected corporation increases with the number of nods ([316], p.221f). That also goes hand in hand with the **complexity** of a supply chain, which can, as well as the **sector** ([78], p.90), lead to higher impacts and longer recovery. But a positive effect of large networks can be financial, physical and psychological **support** from partners, for example in helping to find alternative suppliers more easily ([316], p.209f), when the original source is not going to reopen again. From a precautionary sense, the implementation of **alternative producers** or at least the evaluation whether there are alternatives can help to limit the extent of disasters ([136], p.152; [55], p.55). Also a **diversified supply chain** with partners not solely within a limited geographic area helps to enhance supply chain resilience and reduce recovery times ([316], p.211ff). The goal is, not solely to have partners within the affected area, because the ’**physical proximity** of transaction partners has a negative effect on short-term recovery from region-specific shocks through the disruption of local supply chain networks’ ([316], p.212). Suppliers with strong relationships to **partners outside the affected area** ’[are] [...] less likely to face shortages of supplies or demands and more likely to receive support' ([316], p.221). In general the **distance** to the source of origin has a positive correlation to the value of assets damaged (here and following [78], p.87). Those characteristics can also be summarized under the term **topology**). Of course, a potentially affected area cannot completely be estimated, that is why decentralization aspects should be considered within supply chain design from the start in order to mitigate negative outcomes of disasters. Moreover the **duration** of the experienced effects plays a significant role, which is also influenced by the above mentioned characteristics, like the availability of second sources ([136], p.152). If available, **insurance** can reduce the time to recover, too. There is often 'in developing countries micro and small-business owners rarely [...] insurance to cover natural disasters' ([78], p.65). That is why each region should be analysed separately, considering individual region characteristics, as they can vary considerable between them (see chapter 5). To sum up, 'a proper structure of the chain can enable resiliency and a quicker or even partly a proactive response.' ([319], p.249), what makes supply chain design an integral part of supply chain risk management.

Since a more general approach on country / region level is pursued in this work, and no specific corporation cooperated on supply chain characteristics, the field of investigation would be too large, if all factors affecting the impacts of natural disaster would be included. Therefore the choice of a representing factor is presented in the next chapter.

4.3.2 Recovery times and deviation in delivery times

To assess the impact of natural disasters on supply chain performance, a value that portrays such influences best has to be found. Wildemann (2006a [387]) shows that for procurement risks especially the supplier risk is of relevance (see figure 4.4). This goes along with previous findings, where in supply chain risk assessment approaches the majority focused on supplier risk or supplier selection (what is presented in chapter 4.4.1). Based on that, the assumption comes into place that especially supplier characteristics shall be investigated further.

In more detail Wildemann (2006a) revealed that meeting the agreed quality and the adherence of delivery dates are the most governing factors when logistics risks' impact on performance is evaluated, as can be seen in figure 4.5. While the expected quality is specified very differently in each corporation

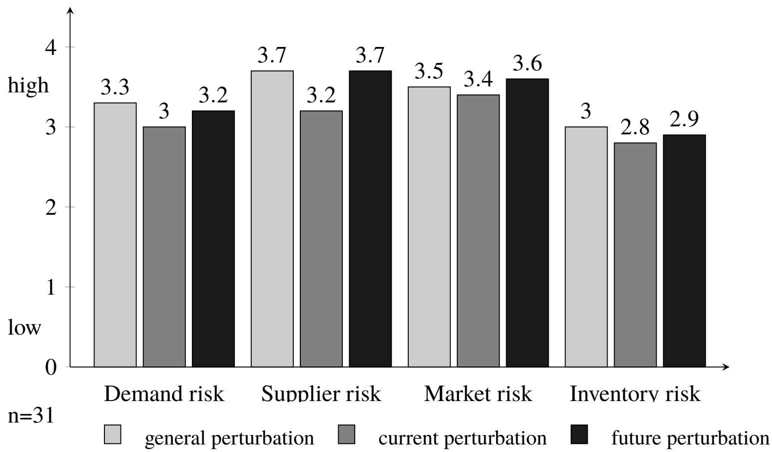


Figure 4.4: Performance impact of procurement risks ([387], p.74)

and context, the delivery time deviation is easily quantifiable (even without deeper knowledge of underlying production specifications). Moreover delivery dates are in most corporations tracked on an ongoing basis ([181], p.27), resulting in an appropriate data basis for further investigations. Beside this are also comparisons between regions and countries regarding delivery time deviations possible, which suits the approach to be developed in this work. Additionally the delivery date deviation is a key performance indicator (KPI - a value measuring the degree of fulfillment for a strategic important corporational activity) and therewith a suitable, and well established, estimator for performance impacts of natural disaster. Even so it must be noted that the survey conducted by Wildemann (2006a) is too small to be representative, the aforementioned remarks are still valid. So delivery time deviations are tracked on an ongoing basis in nearly every corporation, it is a key performance indicator and it enables performance comparisons on a global scale. That is why this indicator is also used within the impact assessment in chapter 6.

Summarized 'the delivery date deviation, [...] the period between the planned delivery date, i.e. the last delivery date accepted by the customer and confirmed by the supplier [...], and the actual date of delivery' ([370], p.23). In reference to Buscher et al. (2010) Λ is the realized delivery time, which is the planned delivery time λ plus the delivery time deviation X.

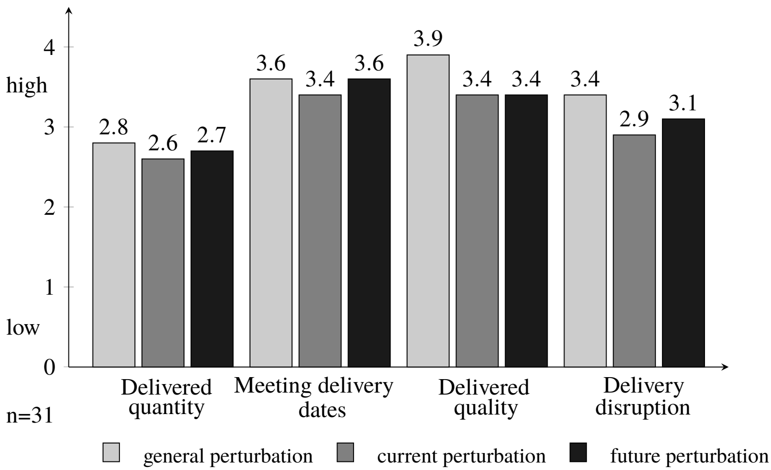


Figure 4.5: Performance impact of logistics risks ([387], p.74)

$$\Lambda = \lambda + X$$

As natural disasters often result in large delivery time deviations, it is also possible that $X = \infty$, describing the total failure of a supplier ([42], p.131f). Also a non-permanent closure can result in deviations, assuming no other measures, like safety stock are in place. Moreover closures are one of the most common effects natural disaster have on business operations ([295], p.22), which can also hamper the ability to remain viable ([314], p.4). That leads to the assumption that a delivery time deviation lasts at least as long as a corporation is closed (while no ex-ante actions are taken). Given all that, business closure times are also incorporated within the model development in chapter 6. Other reasons that can affect a corporations' ability to operate in a normal manner are ([158], p.3; [381], p.8):

- the inability to access the site
- disruptions in electricity supply
- disruptions in water supplies
- disruptions to transportation lifelines

In the end those reasons can result in delivery time deviations or any other performance impact. To define the research gap more precisely (the incorporation of natural disaster in supply chain risk assessments) the literature review on current supply chain and country risk approaches will be presented next.

4.4 Risk assessment approaches in the context of disasters

To evaluate the need to develop a method to assess the impacts of natural disasters on supply chain performance, a literature review on supply chain risk assessment and country risk assessment approaches was completed. This differentiation is chosen, as the supply chain is embedded in the surrounding system of different places, e.g. countries (see chapter 5).

4.4.1 Supply chain risk assessment

Most identified approaches refer to the selection or evaluation of suppliers. This goes along with the aforementioned fact, that especially supplier risks influence the level of performance impacts (chapter 4.3.2).

The first author in table 4.1 Gaudenzi et al. 2006 ([116]) used the **Analytic Hierarchy Process (AHP)** and included four different objectives, which are 'on time delivery', 'order complete', 'order correctness' and 'damage / defect free' which are all presented through the risk areas 'transport', 'manufacturing', 'order cycle', 'ware housing' and 'procurement'. They revealed that 'on time delivery' is the most important sub-objective when it comes to the assessment of supply chain risk, while procurement has a high impact on it. Their findings support the selection of delivery time deviations as estimator for performance impacts of natural disaster on supply chains, as mentioned in chapter 4.3.2 as well. Other authors that used AHP are Bayazit et al. 2005 ([20]), Wu et al. 2006 ([391]) and Zaim et al. 2003 ([395]). For the selection of suppliers Bayazit et al. (2005) incorporated 'logistical performance', 'commercial structure' and 'production', while the first is differentiated in 'delivery performance' and 'cost analysis'. Within 'logistical performance' they found 'delivery performance' to be more important than 'cost analysis'. The authors found 'production', with the most important sub-criteria 'product specifications', the main factor in vendor selection. Wu et al. (2006) is beside this the only reviewed source that distinguishes explicitly between 'internal and external risk' values, and 'controllable', 'partially controllable' and 'uncontrollable' risks. In essence, the authors considered natural disasters explicitly within the assessment. As mentioned earlier natural disasters are part of the group of uncontrollable external risks (see chapter 2.3.2). A case study revealed that 'quality', 'cost', 'continuity of supply', 'on-time delivery' and 'engineering / production' are the key risk factors. But even though external uncontrollable risks were considered the importance of internal risks is rated much higher than external risks. This can lead to the problems already stated in chapter 2.1. Particularly because of their possibly more devastating impact, should external risks not be underestimated nor excluded from supply chain risk assessments.

Table 4.1: Supply chain risk assessment approaches

Approach	**Focus**	**External risks**	**Natural disaster**	**Source**
AHP	supply chain risk	-	-	[116]
AHP	supplier selection	-	-	[20]
AHP	inbound supply risk / supplier risk	x	x	[391]
ANP	selection of logistics service provider	-	-	[154]
Real Option	supply chain risk	x	-	[64]
Indicator	early warning systems for supply	m	-	[187]
Indicator	early warning system / supplier risk	m	m	[167]
Factor Analysis	supplier selection and assessment	x	-	[162]
Factor Analysis	supplier assessment	-	-	[153]
Factor Analysis	supplier selection	-	-	[54]
MAUT	supplier selection	x	-	[184]
Agency Theory	supplier risk, managing supplier behavior	x	-	[400]
Scoring model	supplier risk assessment	x	x	[21]
Scoring model	operational risk assessment	-	-	[312]

Generic aerospace supply chain operation reference model (SCOR)	mitigate supplier risk	m	-	[226]
Different approaches	risk management (KonTraG)	m	m	[103]
Supply network risk tool	risk in supply networks	-	-	[129]

While the aforementioned authors used AHP, Jharkharia et al. 2007 ([154]) applied the **Analytic Network Process (ANP)**, what can be seen as an extension of the AHP, waiving the strict hierarchical order. Within the ANP Jharkhari et al. (2007) compared 'compatibility', 'quality', 'cost' and 'reputation', finding that compatibility between the corporation and service provider is the most important fact. For this reason the selection of suppliers should be a well-made decision within supply chain design, especially with the risk of natural disasters. However, the authors did not consider those risks in their approach.

A **real option approach** is done by Cucchiella et al. 2006 ([64]), and the considered risks divided in internal and external uncertainties, while external criteria refer most to characteristics of the procurement market (see 2.3.2), like the 'political environment'. Beside this they refer to the 'availability of capacity' the most important source of uncertainty, and therewith - like many other authors do - an internal originating risk aspect.

Moder 2008 ([187]) focuses on an overview of all relevant supply chain risks that should be considered in an effective supply chain risk management, i.e. an appropriate early warning system for supplies. As already mentioned also Moder (2008) discovered the risk of catastrophes irrelevant, having a lowish probability. That this could end up in disasters for the forthcoming of a corporation was also already stated (see graphic 2.1 in chapter 2.1). Disaster are at least considered by this source. Köglmayr and Bihler 2009 ([167]) apply an **Indicator based approach**. As they focus on supplier risk, all risks are considered external to the corporation. The risk of natural events is summarized as ecological risk and contains climatological and natural threats, but without any detail on the type of disaster. Even though not explicitly stated, natural threats are underestimated because the evaluation is again reasoned on the probability and potential impact of the triggering event. And as shown earlier, natural disasters occur relatively rarely in comparison to other events, leading to an underestimated risk of natural events.

Another approach focusing on supplier selection and assessment while using **Factor Analysis** is presented by Kannan and Tan 2009 ([162]). Their survey results reveal that aspects like 'geographical compatibility / proximity' as well as 'cultural match between the companies' (regarded as external risks) are ranked relatively low in their importance within supplier selection. While the 'ability to meet delivery due dates' is the most important factor. That fact again supports the choice of deviation in delivery times as estimator for performance impacts of natural disaster on supply chains. Even for the assessment of suppliers is 'on-time delivery' one of three prime aspects. Janker (2008) integrated mostly criteria of a suppliers' capability to meet certain customer demands, like quantity, quality logistics (contains also delivery time aspects) and so on. Although Janker 2008 ([153]) presents an extensive method with a variety of different assessment criteria for supplier evaluation, but external risks are neglected. Factor Analysis is also applied by Choi and Hartley 1996 ([54]), finding that 'consistency' is the most significant term in supplier selection. 'Consistency' consists of 'conformance to specifications, consistency in meeting delivery deadlines, quality philosophy, and prompt response to requests' ([54], p.337f). Again delivery details are ranked top for supplier selection. The only factor that could be classified as an external aspect is the 'geographical location', which goes along with the criteria that Kannan and Tan (2009) mentioned.

Further to that, Min 1994 ([184]) pursues a supplier selection using an **Multi-attribute utility approach**. External facets are 'cultural and communication barriers' and 'trade restriction'. These aspects were already brought up in chapter 2.2, where the factors that lead to increased supply chain vulnerability are explained. However as this work focuses on natural disasters factors like cultural differences are not considered. Other aspects Min (1994) is referring to are the capabilities of a potential supplier in distinct categories. Again 'on-time delivery' is an aim within the category 'service performance', and the second most relevant in international supplier selection. Min (1994) summed it up when he wrote: 'in choosing the most appropriate supplier, the buyer should assess the length of the supply chain as well as the strength of the supplier's commitment for on-time delivery services [...]' ([184], p.27).

Zsidisin and Ellram 2003 ([400]) approved an **Agency theory** investigation. Again the authors are only indicating internal risk sources. Considered risk drivers are 'unanticipated changes in the volume requirements and mix of items', 'production or technological changes', 'price increases', 'product unavailability' and 'product quality problems'. 'Timely, accurate deliveries' are also part of the evaluation.

Within a **Scoring model** Blackhurst et al. 2008 ([21]) investigated internal as well as external supplier risk facts and they additionally incorporated natural disaster risks, like earthquakes, fire and flooding. Fire in this study is the most threatening risk when it comes to disruptions. It is here the first approach identified, that integrates external risks, especially natural events, on a nearly equal weight like internal harms (here 40% resp. 60%). But due to mentioned space limitations the authors just computed an example for quality and disruptions/disasters. That is why no statement on the importance of single risk categories can be found. Nevertheless are within 'logistics' 'on-time deliveries' considered. Thom 2008 ([312]) argues that the most important risk factors in production networks are globalization, transport, customer structure, supplier structure, coordination, natural disaster and terrorism. While natural disaster and terrorism for the surveyed managers play a minor role, as they are seen as less predictable and with a limited influential area. This position though can be very risky, because cascading effects from the area of impact throughout the connected points within a supply chain are totally neglected.

Raj Sinha et al. 2004 ([226]) identified 'standards', 'suppliers', 'technology' and 'practices' as main risk areas, through a **Generic aerospace supply chain operation reference model (SCOR)**. The only possible risks that occur from outside are the stated 'market uncertainties'. These are, following the classification in chapter 2.3.2, 'Supply-chain-external risks, related to specific procurement markets'. In the envisaged FMEA (Failure Mode and Effect Analysis) is the 'failure to deliver on time', reasoned for example through machine breakdown, after 'no clear market perception' from the category 'poor quality of incoming material' the second largest risk source. It is more over to emphasize that Raj Sinha et al. 2004 also differentiated between controllable and uncontrollable risks.

Fiege 2006 ([103]) gives an overview on regulations regarding the **KonTraG** (Gesetz zur Kontrolle und Transparenz im Unternehmensbereich - law that sets standards e.g. on risk management for publicly listed corporations). Even though natural disasters are referred to as relatively rare their devastating impacts are clearly stated and an insurance recommended, because a corporation will unlikely burden the losses on its own. Natural disaster are also defined as threats endangering businesses.

Within the **Supply network risk tool** Harland et al. 2003 ([129]) considered different types of risks from 'risks internal to the corporation' (like operation risks) to 'supply chain external risks, that are related to procurement markets' (like fiscal risks). Risks that are not related to specific procurement markets cannot be found in this literature source. But the different consequences in form of losses are classified, which are 'financial', 'performance', 'physical', 'social', 'psychological' and 'time'.

The review reveals that external risks are very seldom included in supply chain risk assessments. This may stem from the fact that external risks are regarded as less likely than internal risks, even though the impact might be worse - which is often ignored. Only 4 out of 17 methods mentioned (stated as m in table 4.1) at least external risks. While only Wu et al. 2006 and Blackhurst et al. 2008 included natural disasters in their investigation (stated as x), even though they do not give information on performance impacts. It must be said additionally, that the provided literature review is just an excerpt on the variety of risk assessment approaches. But nevertheless it can be seen that most often suppliers are in focus when it comes to risk investigations, what can be justified on the fact, that a firm's performance is often correlated to supplier selection criteria ([162], p.15). That is also why the vulnerability of supply chains to different threats is strongly dependent on supplier characteristics (like the region they are operating in). Furthermore none of the presented approaches considered performance impacts. And what can be seen further, is the high relevance of delivery aspects, as those are stated by almost every author. Which, as already written earlier, emphasizes the choice of delivery time deviations as estimator for performance impacts of natural disaster (chapter 4.3.2). The related mathematics and calculations are presented in chapter 6.

Risk evaluation techniques for country assessment approaches are presented in the following chapter and are analyzed in regards to external risks and natural disaster considerations too.

4.4.2 Country risk assessment

In this sub chapter different approaches are presented that are well-known for several types of worldwide analysis, and there will also be an excerpt on national approaches given (an overview can be seen in table 4.2). The focus lies again on external risks and natural disasters.

The **Worldwide Governance Indicators** [305] provided by The World Bank give a glimpse on the governance quality of alternative countries. The categories that are investigated are: 'voice and accountability', 'political stability and absence of violence', 'government effectiveness', 'regulatory quality', 'rule of law' and 'control of corruption'. All relevant information can be found on the following web page: http://info.worldbank.org/governance/wgi/#doc, explaining the methodology and providing data sheets. As the name of the indicator already reveals natural disasters are not included in these calculations. The external risks that are considered, are, following the definition from chapter 2.3.2), associated to procurement markets resp. the location / country a corporation might be sourcing from.

Another aspect is provided by the **Global Competitiveness Report** [106] from the World Economic Forum. The actual report can be downloaded from: https://www.weforum.org/reports/the-global-competitiveness-report-2017-2018. Also previous reports can be found. Information on the methodology as well as a profound definition of all twelve pillars, that are part of the overall calculation are provided under: http://reports.weforum.org/global-competitiveness-index-2017-2018/appendix-a-methodology-and-computation-of-the-global-competitiveness-index-2017-2018/.
Considered in this index are 'institutions', 'infrastructure', 'macroeconomic environment', 'health and primary education', 'higher education and training', 'goods market efficiency', 'labor market efficiency', 'financial market development', 'technological readiness', 'market size', 'business sophistication' and 'innovation' (those are the twelve pillars). But even though the methodology is explained, it is sometimes not clear how exactly the values are calculated. Additionally, but of course as this is not the aim of this index, natural disasters are excluded. Some of the relevant values for the competitiveness index explain also a certain part of supply chain vulnerability and can therewith be found in the section 5.2.2 dealing with supply chain vulnerability factors.

The **Index of Economic Freedom** [109] persuades also a worldwide view, focusing on economic opportunities and prosperities within an economy. The web page can be reached at: http://www.heritage.org/index/. There are four key aspects incorporated, which are 'rule of law', 'government size', 'regulatory efficiency' and 'market openness'. Each category consists of different single factors that are used for calculation. 'Open markets' subsume for example:

’trade freedom’, ’investment freedom’, ’investment restrictions’ and ’financial freedom’. A disadvantage might be, that for the calculation other indices or reports, like the World Competitiveness Report, are integrated. Moreover the concrete computation is not shown and some of the included values seem very hard to quantify, e.g. ’public trust in politicians’. Therefore it is not replicable where the final values derive from, but they give at least an impression about economic freedom which allows one to compare different countries / economies. Natural disasters are just stated (and just in the text of a country) when they had recently a major impact on the economy of a country, but are not part of the calculation.

Table 4.2: Country risk assessment approaches

Index / Evaluation	**Organization**	**Focus**	**External risks**	**Natural disaster**
Worldwide Governance Indicators [305]	World Bank	Governance quality of a country	x	-
Global Competitiveness Report [106]	World Economic Forum	Competitiveness of a country (economy)	x	-
Index of Economic Freedom [109]	Heritage Foundation	Economic opportunity and prosperity	-	-
Global Terrorism Index [151]	Institute for Economics and Peace	Impact of terrorism in terms of effect on lives, lost, injuries, and property damage	-	-
World Risk Report [38]	United Nations University, Bündnis Entwicklung hilft	Influence of infrastructure on disaster impact, Disaster risk that a country is exposed to	x	x
Credit rating	e.g. Standard & Poors [248]	Likelihood for a country to default	x	-
Natural catastrophes	MunichRe [193]	Natural catastrophe statistics	x	x

On national level (examples)	ERN (Especialistas en Evaluación de Riesgos Naturales) [97]	Natural hazards in Mexico	x	x
	Instituto de Estudios Ambientales (IDEA) (Universidad Nacional de Colombia) [99]	Probability of natural hazards for Columbia	x	x
	Austrian Research Centre for Forests, Department of Natural Hazards [17]	Natural hazards in Austria	x	x

The impact of terrorism is investigated through the Institute for Economics and Peace, publishing the **Global Terrorism Index** [151]. Information that is considered is for example, the socio-economic conditions under which an act of terrorism occurs, trends and the geopolitical drivers. The calculation is based on four weighted indicators for the last five years before the year of consideration. Those are: the ’total number of terrorist incidents in a given year’, ’total number of fatalities caused by terrorists in a given year’, ’total number of injuries caused by terrorists in a given year’ and ’a measure of the total property damage from terrorist incidents in a given year’. The methodology is clearly and comprehensible stated in the appendix, which is a plus compared to other reports. The report is to be found on: http://economicsandpeace.org/reports/. Other reports that are provided through the Insitute for Economics and Peace are e.g. The Positive Peace Report, The Global Peace Index or The Risk Report (which assesses the risk of conflicts and violence). Through the completely different aim, are natural disaster not included.

A **World Risk Report** [38] is published by The United Nations University, Institute for Environment and Human Security and Bü-ndnis Entwicklung hilft. This report shows how infrastructure of a country influences the impact of natural disaster. Beside this the attached World Risk Index calculates a disaster risk by multiplying the exposure of a certain region to natural disaster with the vulnerability of a society. This report is therewith one of the few that incorporates not only external risks that are associated to procurement markets, but also those that are not, like natural disasters. Five types of natural threats are included in the report: earthquakes, floods, cyclones, droughts and sea-level rise. The report and other details can be found here: https://ehs.unu.edu/. For definitions on vulnerability and exposure please see chapter 2. Factors that are used in this work to define the vulnerability to natural disaster can be found in chapter 5.2.2. And an overview on vulnerability factors that are applicable for alternative disaster types can also be found in the appendices A.3 to A.6.

Very common country comparisons are based on the credibility or likelihood of a country to default. A provider is for example Standard & Poors. Ratings from Standard & Poors extend from AAA to D, while AAA means that there is an 'extremely strong capacity to meet financial commitments', means D that there are 'payment default on a financial commitment or breach of an imputed promise; also used when a bankruptcy petition has been filed or similar action taken' ([248]). For a credit rating are five key aspects investigated: 'credit quality of the securitized assests', 'legal and regulatory risks', 'payment structure and cash flow mechanics', 'operational and administrative risk' and 'counterparty risk'. A detailed explanation of all criteria can be found in [247], whereas the exact calculations are not revealed. Germany, for example is rated AAA, The United States of America AA+ (state January 2017). Again natural disasters are not included, as financial aspects come first here. Nevertheless **Credit ratings** [248] enable a country comparison based on financial issues.

Statistics on natural disasters on a worldwide basis are done by MunichRe, called NatCatSERVICE [193]. Disasters are classified in 'geophysical events', 'meteorological events', 'hydrological events' and 'climatological events'. With this analysis tool it is possible to generate maps and graphs that suit the relevant topic best, e.g. the number of flood events for a specified region. Details on disaster types and sub-types can be found in chapter 3.

More granular are indices and **reports on national level**, like the probability of natural hazards for Columbia from IDEA (Instituto de Estudios Ambientales, Universidad Nacional de Colombia) [99], for Mexico from ERN (Especialistas en Evaluación de Riesgos Naturales) [97] or for Austria from the Austrian Research Centre for Forests, Department of Natural Hazards [17]. These three institutions are just an example to show that reports from and for single countries also exist. It is obvious that those investigations are often related to natural disasters, while worldwide approaches are often not.

One of the key findings on worldwide and national reports and indices is therefore: natural disasters are more likely investigated on a minor scale, while worldwide reports focus on other topics than natural disaster. Moreover none of the mentioned approaches has a relation to supply chains or the impact of natural disaster on supply chain performance. It is revealed that for country risk methods the same problem exists like for supply chain risk assessments. While supply chain risk management techniques tend to neglect natural disaster impacts, country approaches have no relation to supply chains. This insight supports the need for development of an assessment approach that evaluates the impact of natural disaster on supply chain performance. The details on the methodology used in this work can be found in chapter 6. It must additionally be emphasized that this review can just be an excerpt, but they show the current state of the art and the methodical gap.

4.5 Résumé

The impact natural disasters can have on supply networks can be manifold. Perturbations in the flow of goods are generally referred to as indirect economic impacts, which was explained in chapter 4. Furthermore supply chain influences are differentiated in disruptions, which are longer lasting and have a wider extent and disturbances. Due to the expected scope it is more likely that natural threats cause supply chain disruptions instead of disturbances. To examine the impact of natural disasters on supply chain performance it is necessary to define what it is exactly that makes a supply chain vulnerable to those events. Therefore the two major components a networks consists of must be analyzed, which are location and transport. As vulnerability while goods are under transportation is very hard to examine, the location can be analyzed by the concept of vulnerability of places (chapter 5). The vulnerability of a production facility or supplier is defined through characteristics of the system / location in question (e.g. a country or state). Those factors can be of social, economic, physical and environmental nature and are quantified using indicators. All factors and indicators used in this work can be found in chapter 5.2.2. Apart from the criteria raised from the surrounding of a location there are also characteristics of the chain that can increase or decrease their vulnerability to certain risks. Since the location shall be in focus here, and no concrete supply chain can be used for evaluations, attributes of the supply chain itself are not incorporated. To assess the aforementioned performance impacts the key performance indicator *deviation in delivery times* is chosen, as it is easily quantifiable, monitored in nearly every corporation and can even be interpreted without deeper knowledge of the underlying production process. Other KPIs, like quality, are too different between corporations. A quality standard that might be acceptable for construction companies might not be so for car manufacturers. The literature review on supply chain risk and country risk approaches revealed that just a few of the existing methods refer to natural disasters perspectively supply chains and none to performance impacts. Therefore a new approach needs to be developed, which is presented in chapter 6.

5 Vulnerability of places - i.e. location

As stated in chapter 4.2 the location is the primary source of investigation here. The concept of vulnerability of places, as well as the application to the research question is explained in the following sub-chapters, followed by a detailed overview of the identified vulnerability factors and their related indicators.

5.1 Concept

Generally speaking 'place' means 'location' ([320], p.8076), which in the context of this work is the location of a production facility or a supplier. In a wider context the location could be a country or narrowed down even further a county or city. Depending on the field of investigation and the system in question the extent of 'place' may vary. As stated earlier, several indicators are available on a country level only (see chapter 3.2). That is why it is useful to start research with a country perspective and try to get a more detailed overview in the next step. Additionally, some factors are only reasonable when they are considered on country level and are not applicable for smaller areas ([383], p.326). The two main components that define place vulnerability are 'those factors of the environment that lead to increased potential for hazardous events to occur, [...]; and those characteristics of the people and places that make them less able to cope with and rebound from disaster events' ([68], p.106). Those factors can be classified in social, economic, physical and environmental vulnerability criteria, as can be seen in figure 5.1 ([29], p.932; [332], p.41; [333], p.32; [166], p.193). The four categories enable thereby an explanation of differences or inequalities between places ([67], p.243). Even for nearly similar systems the vulnerability can be divergent. This makes it necessary to analyze every place separately and to not expect similarities ([67], p.242; [320], p.8078).

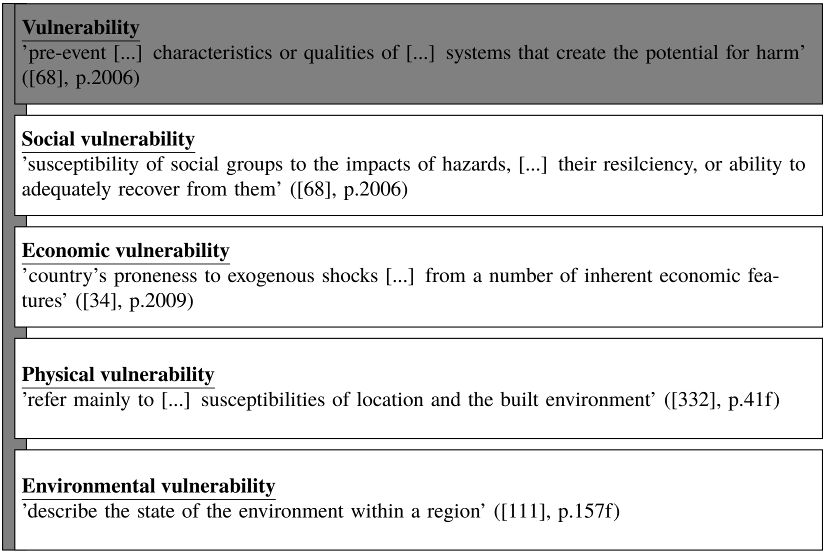


Figure 5.1: Vulnerability of places

The overall vulnerability contains all 'pre-event, [...] characteristics or qualities of [...] systems that create the potential for harm' ([68], p.2008). On one hand it can be the characteristics of the region a supply chain is embedded in, and / or on the other hand it can be the characteristics of the supply chain itself (see chapter 4.3.1). So the term 'system' can have different meanings. This work refers to the location as the focal point. **Social vulnerability** is understood as the 'susceptibility of social groups to the impacts of hazards, [...] their resiliency, or ability to adequately recover from them.' ([68], p.2006). As this definition implies 'social vulnerability [...] [is] linked to the level of well-being of individuals, communities and society' ([332], p.42). Often social susceptibility is the result of social inequalities and is described using 'individual characteristics of people [like] [...] age, race, health, income, type of dwelling unit [and] employment' ([67], p.243). A detailed review on social factors can be found in chapter 5.2.2. From an **economic** point of view the **vulnerability** is a 'country's proneness to exogenous shocks [...] from a number of inherent economic features' ([34], p.2009). Of course smaller entities than countries can also be considered, but this requires respective data. Factors are the 'economic status of individuals, communities and nations' ([332], p.42) here, which are defined in more detail in chapter 5.2.2. The **physical factors** 'refer mainly to considerations and susceptibilities of location and the built environment. It may [also] be described as 'exposure" ([332], p.41f). Single criteria are for example building and infrastructure characteristics, as shown in chapter 5.2.2. 'Exposure describes the elements at risk to a natural disaster' (here and following [383], p.329f), while physical proximity to the source enhances the risk. For example 'the susceptibility of a human settlement to be affected by a dangerous phenomenon due to its location in the area of influence of the phenomenon' ([46],p. 13). Thus, location is strongly related to topology and shall not be mistaken by the total vulnerability of a location. The '**environmental vulnerability** describes the state of the environment within a region' ([111], p.157f), which is the ecosystem that surrounds the system under consideration. Examples for relevant factors are the state of environmental degradation or the number and area of protected territories (see chapter 5.2.2). For the analysis of different locations, 'each factor is characterized by a set of proxy indicators that are generalized at the national and sub-national scales' ([47], p.113). The chosen indicators are, apart from the aforementioned vulnerability factors, presented in the chapters 5.2.2 to 5.2.2. A complete overview of identified factors and indicators (from the intensive literature review) can be found in the appendices A.3 to A.6.

To gain a profound understanding of the inherent vulnerability of a place, it is important to note that 'social, economic, [physical] and environmental sectors are all interlinked, [and] reliable indices should take all these factors into consideration' ([121], p.3). The interaction of vulnerability factors can be seen in figure 5.2.

Additionally the characteristics of the disaster, like probability (frequency), intensity, geographical extent and duration are part of the investigation, as the possible negative outcomes are also dependent on those ([332], p.36; [166], p.192; [383], p.329). Moreover, the type of the disaster can be of relevance ([59], p.16; [333], p.32; [35], p.3), caused by differences for example in onset and duration. For example droughts are the result of long-term developments (time with low precipitation), while floods have a very sudden onset. Details on that can be found in chapter 3.1. The necessary information on natural disaster can be derived from historical data ([29], p. 932; [238], p.43).

After defining the prerequisites for appropriate indicators, subsequently the factors of the four vulnerability categories with their related indicators will be presented.

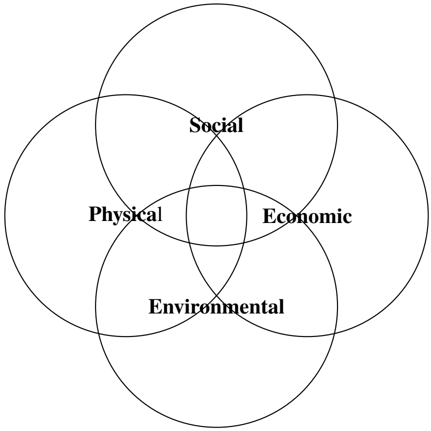


Figure 5.2: Interaction of vulnerability factors ([332], p.41)

5.2 Vulnerability indicators

To evaluate the vulnerability of a location, it is firstly necessary to identify the relevant factors and indicators, which are presented in the following chapters. As this work is not focusing on specific disasters, a more generic approach was chosen. This means that the factors shown in chapter 5.2.2 to 5.2.2 are those mentioned in the literature for all types of disasters. And 'there are certain factors that are likely to influence vulnerability to a wide variety of hazard' ([36], p.153). Additionally a more general method is useful, when 'we wish to undertake comparative assessments of vulnerability at the national level' ([36], p.153), which is intended as a first step, as already mentioned in chapter 5.1. Investigations on county or city level might be step two. Nevertheless, a detailed overview on disaster specificities in vulnerability indicators is given in appendix A.3 and the following.

5.2.1 Prerequisites for indicators

Firstly it must be clear which prerequisites indicators have to be fulfilled, to be applicable. As mentioned several times the selection of factors and indicators generally 'depends on the purpose of the study, the research discipline being explored and the final application' ([89], p.14). Indicators are, despite other methods, used here, as they 'seem to be useful media, because they synthesis complex state-of-affairs such as the vulnerability of regions, households or countries into a single number that can be easily used [...]' ([140], p.198). They enable decision makers to reduce 'complexity, measuring progress, mapping, and setting priorities' ([70], p.603) and are 'useful to communicate complex issues from science to policy or the general public' ([140], p.204). But it is important to note, that 'indices reflect only the current state of the environment and must be constantly reviewed to ensure accuracy.' ([121], p.2f). Therefore, the historical values are used in chapter 6 only as a starting point. Moreover, 'vulnerability indicator[s] [do] [...] not give us information on when in the future harm will occur' ([140], p.201), they express merely the suspectibility to possible future harm from natural disasters.

To choose suitable indicators the following aspects must be taken into account ([91], p.20 [1]; [155], p.188; [89], p.15f; [383], p.330):

- data availability and quality
- recognition
- quantitativeness
- suitability for international and temporal comparisons
- simplicity and ease of comprehension
- affordability
- objectivity

As not all items in the stated literature are suitable for the research focus, only fitting characteristics were chosen. Data availability and quality refers to the aspect that data for all indicators must be available and that the source must be reliable. Apart from this it is essential that the indicators already 'recognised by researchers [are] as important'([89], p.15f) for the evaluation of vulnerabilities. Quantitative values are more comprehensive and reduce the influence of subjectivity within analysis, leading also to the aspect of objectivity. Moreover quantitativeness encourages a wider indicator acceptance ([89], p.15f). As a comparison between different regions (e.g. countries) is planned, the indicators must be available for all regions and times in question, enabling an international or inter-regional comparison. Additionally the indicators must

[1] The original source, stated in UNEP 2006 is not available anymore. That is why the information is taken from this source.

be easy to understand, so that they are 'useful to the public, policy-makers, and programme administrators' ([91], p.20), or in general the decision makers - which are probably the supply chain risk managers in the context of this work. Last but not least data must be affordable. It is not useful when the costs for data purchases exceed the benefits.

The identified 'vulnerability indices can [therefore] help [to] identify and prioritise vulnerable regions, [...] raise awareness, and can be part of a monitoring strategy' ([202], p.23). All vulnerability factors and their indicators presented in the following chapters are derived from an intensive literature review, taking the aforementioned prerequisites into consideration. Following the classifications found in the literature sources the identified vulnerability factors are also differentiated in social, economic, physical and environmental aspects.

5.2.2 Indicators

Factors of social vulnerability

One important aspect to evaluate the differences in vulnerabilities to natural disasters, are social factors. 'Social vulnerability is [often] the product of social inequalities. It is defined as the susceptibility of social groups to the impacts of hazards, as well as their resiliency, or ability to adequately recover from them' ([68], p.103). To understand dissimilarities it is therefore necessary to evaluate the system (place) in question. 'What needs to be analyzed is how the structure of a society determine[s] the way in which a hazard is likely to affect it' ([45], p.26). Social facets can thereby explain the contrasts between or within regions (in combination with the later mentioned economic, physical and environmental factors) concerning the extent of natural disaster impacts ([68], p.102, [45], p.14, [392], p.382, [333], p.18, [244], p.101). Furthermore, the social system itself can be the source of vulnerability ([45], p.14). Factors contributing to the vulnerability of people / societies are shown in table 5.1. It is important to note that single factors cannot explain the overall vulnerability of a person, it is more often the interaction or combination of several factors ([89], p.17). Figure 5.3 portrays the percentage of authors referring to a certain category of social factors [2]. What can be seen is, that individual's

[2] The values presented in the graphic show the percentages for all identified literature sources, not just the ones stated in table 5.1. Moreover are different sources counted once within each factor

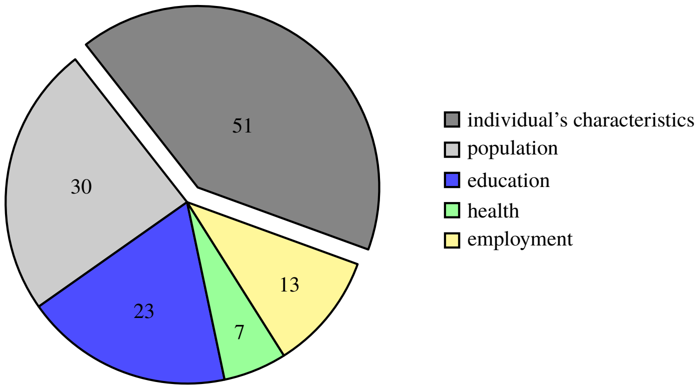


Figure 5.3: Social vulnerability factors: percentage of authors referring to different characteristics

characteristics and population aspects are stated most. These and all other single entries are now discussed in detail.

Age and **gender** are the factors that are stated most in the literature, and it is assumed that they can in fact explain the majority of differences in social susceptibilities. Often gendered vulnerability is the result of 'historically and culturally specific patterns of relations in social institutions, culture and personal lives' ([93], p.159). It is expected that women are more vulnerable, due to their role as caregiver, caring for children, elderly, whole families, or disabled, as well as due to lower wages and sector-specific employment ([133], p.7, [107], p.36, [71], p.21, [189], p.238f, [332], p.42, [67], p.246).

In addition, this role results in some societies lack of education and also restricted mobility, enhancing their vulnerability even more. The indicator used is 'gender per percentage of population', while a higher percentage of females concludes with more vulnerability. In addition elderly and adolescents are in need for help when a disasters strikes, but are lacking the necessary physical resources to respond ([176], p.812, [71], p.21). This goes along with the aforementioned aspect that women rather than men care for them, making women more vulnerable. Another aspect is 'the elderly [...] tend to be more reluctant to evacuate their homes in a disaster' ([71], p.21). The higher the percentage of younger or older people, the higher a society's vulnerability.

category and not just once for the main category (here social), resulting in a sum greater than one in the pie chart. This aspects are valid for all percentage analysis.

Furthermore **population growth** and **density** can be used to describe the social vulnerabilities within a region or place. With faster population growth, the inherent susceptibility increases as well, as the surrounding structures are often too slow to adapt ([67], p.248). Apart from that, the need for general care and post-disaster help increases in areas with high population densities. And on top of that more people are affected when they are densely populated near a triggering event. This is accompanied by the fact that 'the top countries at risk in terms of killed per year are the most populated countries (China, India, Indonesia, Bangladesh), whereas small islands states [...] come first in terms of killed per million inhabitants per year' ([217], p.1156). Indicators are the number of housing units (giving an overview on the density of built structures), population density (explaining how much people live in a certain area) and birth rates.

Table 5.1: Factors of social vulnerability

Factor	Indicator	Source
individual's characteristics		
age	percent of population under 5 and above 65; median age	[392], p.382ff; [59], p.22; [217], p.1; [67], p.243ff; [71], p.21; [139], p.7; [32], p.1618; [332], p.42; [29], p.934; [138], p.27; [205], p.82; [126], p.115; [41], p.143; [68], p.103; [89], p.5; [237], p.88ff; [389], p.6; [47], p.113; [333], p.102 [243], p.63; [132], p.2; [190], p.34, 63f, 101ff
gender	gender per percentage of total population	[93], p.158f; [332], p.42; [29], p.934; [67], p.245ff; [237], p.89ff; [139], p.7; [392], p.381f; [71], p.21; [45], p.23; [96], p.119f; [133], p.5ff; [107],p.35f; [189], p.238f; [138],p.27; [65], p.533; [205], p.82; [126], p.116ff; [94], p.131ff; [41], p.137ff; [89], p.5ff; [132], p.2ff; [68], p.103ff; [383], p.330; [243], p.63; [389], p.7ff, 15
population		

population density	number of housing units per square mile, total human population density (persons/km^2)	[398], p.254; [29], p.934; [67], p.250; [190]; p.100f; [121], p.6; [163], p.32; [243], p.63; [25], p.276; [161], p.17; [217], p.1; [59], p.22; [378], p.1932; [333], p.3, 102
population growth	birth rate (number of birth per 1000 population)	[392], p.383; [71], p.21; [29], p.934; [67], p.248 ff; [25], p.276; [127], p.154; [126], p.117; [161], p.17; [217], p.1; [121], p.6; [32], p.1618; [333], p.102
education		
education	education expenditure as % of GNP	[392], p.381; [71], p.21; [139], p.7; [332], p.42; [126], p.116f; [67], p.248 ff; [1], p.81; [237], p.85ff; [166], p.193; [47], p.113; [333], p.102; [218], p.54; [25], p.276; [217], p.2
employment		
employment	% unemployed; percent of population participating in the labour force	[71], p.21; [139], p.7; [29], p.934; [67], p.243ff; [183], p.239; [333], p.102; [149], p.20; [190], p.34, 63
health		
access to medical services	number of physicians per 1000 population	[392], p.383; [67], p.248ff; [71], p.21; [137], p.157

Social vulnerability also depend on the level of **education**, measured by governmental expenditures, showing the social development of a society. A higher educational level is linked to greater expected earnings (here and following [67], p.248), which is enabling a society a better compensation of disaster impacts. While low educational levels may restrain the ability to understand warnings, and in the aftermath of an external shock may complicate applications for financial relief. The status of **employment** also influences social vulnerability, as people that are already in the need of help, suffer more often, e.g. due to a lack of financial resources for recovery. In general 'poor people have less money to spend on preventative measures, emergency supplies, and recovery efforts. Although the monetary value of the economic and material losses of the wealthy may be greater, the losses sustained by the poor are far more devastating in relative terms' ([71], p.20). But even 'the potential loss of employment following a disaster exacerbates the number of unemployed workers in a community, contributing to a slower recovery from the disaster' ([67], p.247). As '**health** care providers including physicians, nursing homes, and hospitals are important post-event sources of relief' ([67], p.248f), this aspect is pictured in access to medical services. 'The lack of proximate medical services will lengthen immediate relief and longer-term recovery from disasters.' ([67], p.2488f).

In summary, social vulnerability is mostly linked to the level of development ([217], p.1149), which is also dependent on economic factors, which are explained in the following chapter 5.2.2.

Factors of economic vulnerability

Economic vulnerability is described as 'a country's proneness to exogenous shocks [...] from a number of inherent economic features' ([34], p.232). In contrast to chapter 5.2.2, in which individual characteristics of people and society were discussed the focus will now shift to economic features (see table 5.2). Those factors can refer to economic attributes of the whole community, population groups or individuals ([111], p.157) and explain the varying impacts of disaster on economic activities ([316], p.211).

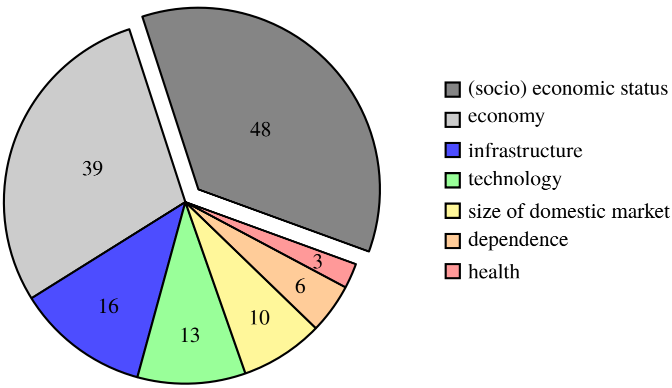


Figure 5.4: Economic vulnerability factors: percentage of authors referring to different characteristics

Figure 5.4 shows that especially the (socio)economic status and the economy itself are the prime contributing factors to economic vulnerability. As 'wealth enables communities to absorb and recover from losses more quickly' (here and following [67], p.246ff) the **economic capacity** is a good indicating factor of economic strength. But even though a high capacity suggests enough financial resources, there are normally more assets at risk to natural disasters, resulting in higher material losses. Meanwhile poorer societies often face higher losses in terms of affected or killed people and livelihoods. That is why 'in less developed regions of the world, low losses reflect a deficit of infrastructure and economic assets rather than a low impact' ([332], p.13). 'Obviously, similar exposures with contrasting levels of development lead to drastically different tolls of casualties' ([217], p.1149). Infrastructural aspects are hence incorporated as **transport structures** and **accessibility of resources**. Moreover, the availability of transport infrastructure (even in the case of disasters) is an integral asset to prevent deviations in delivery times (please see chapter 4.3.2). Apart from this wealth can be expressed in **health expenditures**, showing if economies can afford to care to a certain extent for their population.

Table 5.2: Factors of economic vulnerability

Factor	Indicator	Source
(socio) economic status		
economic capacity	GDP per capita (current US$)	[318], p.40; [47], p.113; [217], p.1; [218], p.54; [25], p.276; [149], p.20; [166], p.193; [45], p.26f; [1], p.81 [333], p.3, 102
size of domestic market / resource base		
small size	population, land area; gross national product (GNI)	[166], p.193; [45], p.26f; [333], p.3
technology / research		
research and development	R&D investment (% GDP); researchers in R&D per million population	[166], p.193; [45], p.26f; [1], p.82; [243], p.68
infrastructure / access to resources		

transport network	roadways; waterways; railways [in km]	[190], p.35
infrastructure / accessibility	access to electricity; access to improved sanitation facilities; access to improved water source (for all 3: % total population)	[237], p.88ff; [166], p.193; [45], p.26f [243], p.61
economy		
type of economic activities	%age of arable land, arable land (in hectars); %age of urban / rural population	[217], p.1, [333], p.3, 102
dependence on primary commodities	agriculture (% of GDP)	[217], p.1; [333], p.102; [166], p.193; [45], p.26f; [29],p.934; [67], p.250; [383], p.330; [1], p.82; [243], p.66ff; [47], p.113
health		
health expenditures	public expenditure on health as per cent of GDP	[218], p.54
dependence		
export concentration	exports of goods and services (% of GDP)	[166], p.193; [45], p.26f
dependence on strategic imports	imports of goods and services (% of GDP); energy imports, net (% of energy use); food imports (% of merchandise imports); ores and metals imports (% of merchandise imports)	[166], p.193; [45], p.26f

The **size of the domestic market** and the **availability of resources** is also of relevance, as a high dependence on other countries enhances the occurrence of side-effects. Even if an economy is not directly affected, the indirect effects to the flow of goods can be tremendous (see chapter 4). Meanwhile 'countries with a relatively small domestic market have very few options but to resort to exports, [...] those with limited natural resources tend to be highly dependent on imports' ([34], p.232). Based on that, the size of an economy, as well as **import and export concentration** are included in further investigations. Additionally the **type of economic activity** is of relevance as economies are more vulnerable when they are dependent on primary commodities. Which are often the first affected when a disaster strikes. Also 'a singular reliance on one economic sector [...] creates a form of economic vulnerability for countries' ([67], p.253). Indicators are the percentage of urban and rural population as well as the percentage of arable land.

The stability of economies also has a strong influence on procurement policies and strategic sourcing decisions ([72], p.113f), as it is always desirable to source in more stable countries, minimizing the own supply chain risk. As can be seen in comparison to chapter 5.2.2 some of the sub-categories double, like health. If this is the case, the indicator does refer to different aspects of vulnerability, which can be social, economic, physical and environmental vulnerability. In this example, the 'public expenditures on health' are related to economic capabilities (so economic vulnerability) and the 'number of physicians' explain the cover of medical care (so social vulnerability).

The third category, physical vulnerability is next explained.

Factors of physical vulnerability

Physical factors explain the susceptibilities of locations (topology) and the built environment ([332], p.41f, [111], p.157). Once again population aspects in the literature are stated most, followed by infrastructure, as can be seen in figure 5.5. The relevant vulnerability factors and their indicators are stated in table 5.3.

A high concentration of people (**population density**) is associated here with unsafe physical settlements ([243], p.63), making them more vulnerable to the impacts of disaster. But as the factor 'population density' was already discussed in chapter 5.2.2 it will only be mentioned here and will not be repeated. Strongly related to dense concentrations of people is also the level of **urbanization**.

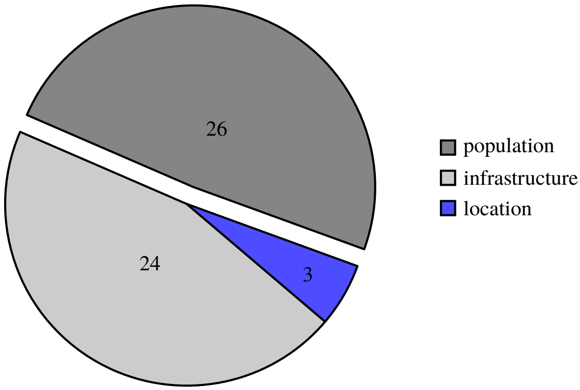


Figure 5.5: Physical vulnerability factors: percentage of authors referring to different characteristics

Table 5.3: Factors of physical vulnerability

Factor	**Indicator**	**Source**
infrastructure		
puplic infrastructure	road density (km of road per 100 km^2 of land area)	[166], p.193; [36], p.155; [138], p.27; [398], p.254; [332], p.42; [213], p.1393; [1], p.81f; [318], p.40; [47], p.133
population		
population density	residents / km^2	[166], p.193; [383], p.330; [333], p.102; [332], p.42; [195], p.182ff
urbanization	percent rural / urban population	[166], p.193; [186], p.19, 27; [243], p.67; [29], p.934; [333], p.5; [237], p.90 [67], p.243ff
location		
location of dwelling	(urban/ rural) population living in areas where elevation is below 5m (for all 3: % of total population)	[237], p.90ff

Reasons for the impairing effect of urbanization are, the subsequent growth of urbanized areas, which can be seen in higher risk areas, as for instance in coastal metropolises like Houston (here and following [186], p.27). Houston also recently came into focus when Hurricane Harvey made its way through Texas ([191]). Moreover, the high concentration of assets is reinforcing vulnerability, as more value can be affected within a limited geographical area. Additionally the replacement rate of old buildings can often not keep up with urban growth, resulting in a high level of dwellings that do not meet current standards.

To gain the true coverage with infrastructure, the available kilometers (already stated in chapter 5.2.2) are here set in ratio to the land area. The greater the coverage, the lower a region's vulnerability. The aspect of **dwelling location** is included, because floods are the most frequent natural disasters (see chapter 3.2.1) all over the world. And as more people continue living in areas below 5 meters (N.N.) there is a higher risk of flooding and thus higher expected disaster impacts for that region. The last of the four described vulnerability categories - environmental vulnerability - contains aspects of the environment, which are discussed in the next paragraph.

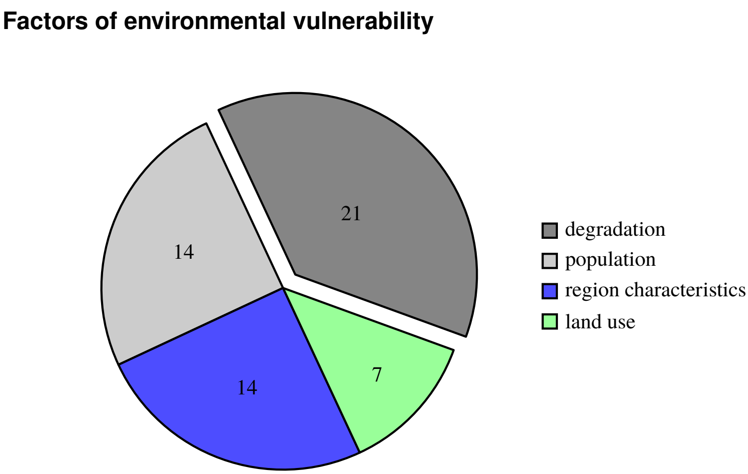


Figure 5.6: Environmental vulnerability factors: percentage of authors referring to different characteristics

Environmental vulnerability ’describe[s] the state of the environment within a region’ ([111], p.158) and ’is related to the risk of damage to the natural environment’ ([195], p.182). All categories within this category can be found in table 5.4. Degradation in this category is the most important facet of vulnerability and 21 % of the authors in the literature review referred to it (figure 5.6). Damage or irreversible change to the ecosystem is incorporated as **environmental degradation**, lowering the resistance to natural disaster. Another factor of environmental stress is **ecology**, referring to the marine and terrestrial protected areas in relation to total land area. Where ’reserves may be one of the few ways managers could off-set some other environmental damage and build resilience against natural events that can damage the environmental support system’ ([100]).

The number of **borders** captures the risk of neighboring effects. The more adjacent countries a country has, the greater the risk of trans-boundary impacts (here and following [100]). Also, the country dispersion is of importance, as highly dispersed countries are also more prone to effects from other countries and often lack natural barriers to environmental risks. Regarding to floods also the length of coastlines is included, leading to higher susceptibility the longer a coast line ([333], p.3). Similar to the indicator *population living in areas where elevation is below 5 meters (N.N.)* from the previous chapter, the land area under this sea level is at risk here. The higher the percentage of land area below this value, the higher the risk for environmental damage through flooding within the observed area. Additionally a larger **land** mass enables a better compensation of negative effects from disasters, because more non-affected area is available. Likewise **population density** is for social and physical susceptibilities, an important variable of environmental vulnerability, what makes population the most influencing factor for the overall vulnerability. Population density here is ’a proxy measure for pressure on the environment resulting from the number of humans being supported per unit of land. A higher number of people increases pressure on the environment for resources, for the attenuation of waste and physical disturbance of the environment’ ([100]).

Table 5.4: Factors of environmental vulnerability

Factor	Indicator	Source
land use / land cover		
ecology	terrestrial / marine protected areas (% of total area); forest area / arable land (% of land area)	[36], p.155; [1], p.82
population		
social pressure	total human population density	[1], p.82; [142], p.543; [100]; [36], p.155
degradation		
country wide / regional environmental degradation	agricultural irrigated land (% of total agricultural land)	[392], p.381; [332], p.42f; [29], p.933; [25], p.277; [190], p.36; [100]; [237], p.91
regions characteristics		
lowlands	(urban / rural) land area where elevation is below 5 meters rural land area where elevation is below 5 meters (for all 3: % of total land area)	[100]
borders	number and length of land and sea borders shared with other countries	[100]
country dispersion	ratio of length of borders (land and maritime) to total land area	[100]
land area	total land area (km2)	[100]; [243], p.68
coasts	km of coastline (scale by land area)	[36], p.155; [1], p.82

Finally it can be stated that there are numerous factors for the different vulnerability levels of distinct places and that the research focus, as well as the underlying system, must be considered. While those aspects that are most often considered in the literature and that are related to the topic - impact assessment of natural disaster on supply chain performance - are discussed here, other indicators are in place as well. A complete overview over the factors identified within the literature review can therefore be found in the appendices A.3 to A.6. The influence of the mentioned vulnerability indicators on supply chain performance will be tested in chapter 6.

6 Impact assessment

Below are the steps of the **S**upply **C**hain **Perform**ance Impact Assessment of **N**atural **D**isaster (SCperformND) described in general, followed by a mathematical foundation of each step. The calculation follows the Loss Distribution Approach (LDA), quantifying delivery time deviations as estimator for the performance impact caused by natural disasters. Steps are:

1. the identification of business closure times
2. the identification of vulnerability indicators
3. the determination of the relation between business closure times and vulnerability indicators
4. the frequency assessment of natural disaster
5. the calculation of the compound distribution.

6.1 Methodology

The KPI 'deviation in delivery time' will be used as an estimator for the performance impact natural disaster can have on supply chains. Please see the references made in chapters 4.3 and 4.3.2 for further explanations. To compute those impacts a Loss Distribution Approach (LDA) was chosen, as this method allows a combination of severity (the extent of delivery time deviations) and probability (the frequency of deviations), resulting in a compound distribution which states the frequency of certain deviations for distinct locations.

Subsequently necessary steps for the methodology will be described in general, followed by a mathematical foundation in the next chapter.

Step 1 - Identification of business closure times

To repeat, 'the delivery date deviation, [...] is the period between the planned delivery date, i.e. the last delivery date accepted by the customer and confirmed by the supplier [...], and the actual date of delivery' ([370], p.23). Since the deviation is referring to a time horizon, the loss / severity (distribution) to be determined is also expressed in entities of time ([393], p.123). The severity distribution is one part of the Loss Distribution Approach mentioned above, stating the extent of delivery time deviations.

As there was no corporation specific delivery data available, due to already stated reasons, and in the conducted literature review no source on delivery time deviations caused by disasters could be found, the assumption is made that the deviation lasts at least as long as a corporation is closed after a disaster hit. A consequence is the business closure time representative for the deviation in delivery time. Business closure time is understood as the time a corporation needs to reopen after being affected by a disaster, while during the interruption 'no business activities, such as production or service, are possible' ([170], p.12). Apart from the assumption it is necessary that no preventive measures are in place, as no statement about it could be made. A reason for that could be that measures are not known and their influence on delivery time deviation reductions is not jet analyzed. Even within the extensive literature review done in this work, just a few authors could be identified that investigated affects of natural disasters on business closures, resulting in 32 studies that are used for the approach in this work. The small number of sources is not surprising as the affects of natural disasters on businesses are generally underestimated and mostly people's safety instead of business continuity is addressed when it comes to prevention (see chapter 1.1). But even though no individual delivery time data could be used in this work, it is again important to note that this information is tracked in nearly every corporation and can easily be applied within the introduced method.

Step 2 - Identification vulnerability indicators

To explain the differences in delivery time deviations after a catastrophe in distinct locations, it is necessary to identify the factors which can lead to varying vulnerability levels. All factors and their indicators used in this work have been presented in chapter 5.2.2 and are based on an intensive literature review.

The four major categories are social, economic, physical and environmental factors with the relating subcategories shown in figure 6.1.

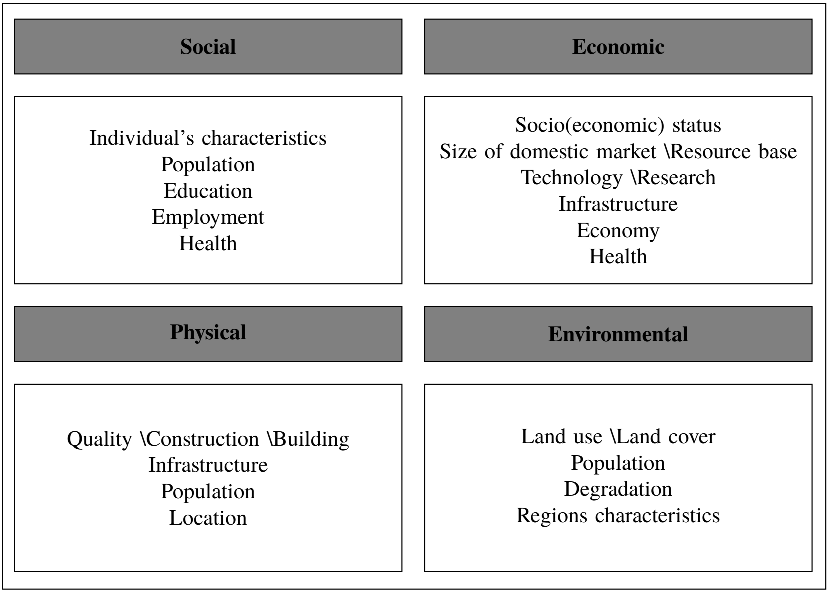


Figure 6.1: Vulnerability factor categories

Step 3 - Relation between business closure times and vulnerability indicator

To find indicators for different business closure times for varied places, a linear regression model is used. All vulnerability indicators identified in step 2 (out of the four vulnerability factor categories - social, economic, physical and environmental) are tested as explaining variable. The detailed computation for that step can be found in chapter 6.4.

Step 4 - Frequency of natural disaster

For the performance impact assessment the probability of the triggering event must be determined, which is defined as 'the number of times it occurs within a specified time interval' ([178], p.359). The distribution is referred to as frequency and is the second part of the LDA. The frequency distribution indicates the probability of business closure, respectively delivery time deviations. All relevant data for the frequency analysis is obtained from statistical time series ([79], p.3; [119], p.xv).

Step 5 - Compound distribution

The compound distribution is calculated combining the severity distribution (the business closure times from step 1) and the frequency distribution (the frequency of natural disaster from step 4). The distribution explains the probability of certain extents of closure times after a natural disaster. Whereby the business closure times are determined through the different vulnerability indicators from step 2, leading to varied distributions for distinct locations.

Furthermore the mathematical formulations are demonstrated for the above introduced steps.

6.2 Step 1 - Identification business closure times

The relevant data on business closure times was, according to the methodology description in chapter 6.1, gathered in a literature review, giving the results shown in table A.8 in the appendix. The general procedure, using a probability mass function, to reach comparability between the stated values in the literature review is described below. Exemplary figure 6.2 shows the determination of a probability mass function and a cumulative distribution function. Part (a) states the given data - the time a certain amount of corporations closed, for example did 50% not close while 10% closed for 3 days. The number of days a business closed after a natural disaster hit is defined by the discrete random variable Z. The probability mass function (illustrated as (b) in figure 6.2) is a function given by

$$f_Z(z) = P(Z = z) \tag{6.1}$$

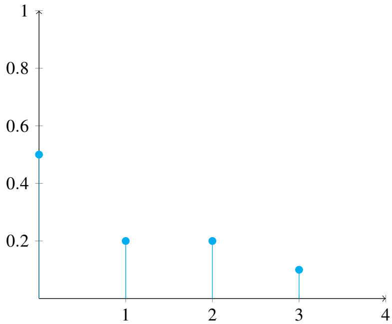
where f_Z presents the probability that a business closed for z days. The cumulative distribution function of Z (part (c) in figure 6.2) is a function given by

$$F_Z(z) = P(Z \leq z) \tag{6.2}$$

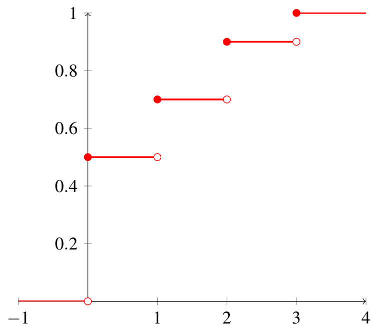
where F_Z defines the probability that a business is not closed for more than z days. For example is $F_Z(2) = 0.9$, meaning that with 90% probability closure time is 2 days or less.

closing time in days	share
0	0.5
1	0.2
2	0.2
3	0.1

(a) data source



(b) probability mass function



(c) cumulative distribution function

Figure 6.2: Visualisation step 1

Because the varied literature sources used partially very different levels of detail to describe business closure, ranging from a single percentage of closed corporations to several gradations within one day, the mean closure time (MCT) is introduced and used for further calculations. As the MCT could be calculated for all sources, it enables the aforementioned comparability between the differing studies. Other values, for example the standard deviation etc. were tested, but could not be computed for all sources.

Given f_Z as the probability mass function of Z, the MCT_i is defined as the expected value of Z_i and is calculated for every data source i as follows:

$$MCT_i = \mathbb{E}[Z_i] = \sum_{z \in \mathbb{R}} z f_{Z_i}(z) \tag{6.3}$$

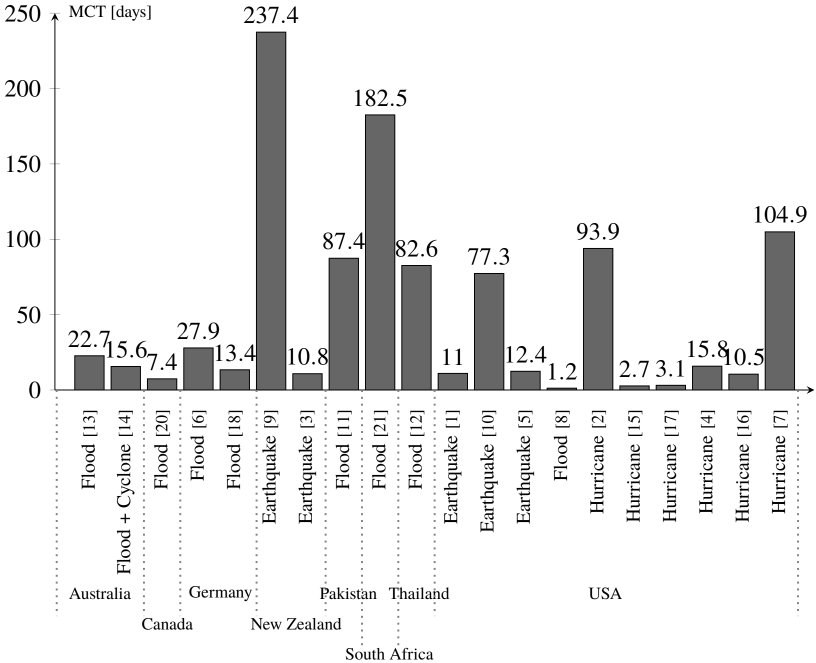


Figure 6.3: Mean closure time per event-ID

If more than one data set was available for the same event, the MCT is the arithmetic mean over all studies. With n as the number of sources utilized, the MCT is calculated as:

$$MCT = \frac{1}{n} \sum_{i=1}^{n} MCT_i \tag{6.4}$$

Figure 6.3 illustrates the mean closure times for all investigated events, as well as the respective disaster type and the affected country. For a repetition of disaster types, please see chapter 3.2. The mean closure time values are shown in appendix A.8.

As a next step factors which serve as explaining momentum for varied mean closure times between distinct locations are identified.

6.3 Step 2 - Identification vulnerability indicators

According to step 1, the indicators (the values that measure the factors in figure 6.1) for the nine countries indicated, for which business closure times were investigated in the 32 studies mentioned above. Considered countries are The United States of America, Germany, New Zealand, South Africa, Pakistan, Thailand, Australia, Canada and The United Kingdom. The underlying disasters and the year the event took place can be found in table 7.2 in chapter 7.1 and the literature sources utilized in appendix A.10.

As the indicators change over time and the data on business closure times are from a specific event year, it was necessary to search the data from the respective event year, too. That is all the more important, as finally a statement shall be given on future delivery time deviations, given the current vulnerability indicators. The intensive research resulted in more than 3500 single data entries, for the indicators in table 6.1 which had been already explained in chapter 5.2.2. For collection and calculations is Microsoft Excel®2010 used. Despite the effort to gather all indicator values from the respective event year, it was sometimes not possible. In those cases the next data year was chosen, if the deviation was one year maximum, as it is assumed that a possible change is acceptable within one year. For greater deviations the available data has been used to update or backdate to the event year, up to a deviation of eight years give or take. Tests with a wider time interval resulted in a total change of the underlying regression (step 3), so a range of eight years was chosen. Figure 6.4 illustrates the realized linear interpolation to calculate the missing data points.

For a value in time α between a time a_0 and a_1 is $f(\alpha)$ with $f(a_0)$ and $f(a_1)$ approximated through ([384], p.16):

$$f(\alpha) = f(a_0) + \frac{f(a_1) - f(a_0)}{a_1 - a_0} (\alpha - a_0) . \tag{6.5}$$

Unfortunately it was still not possible to gather the entire value set for the United Kingdom from 1978 and 1979, consequently the United Kingdom had to be excluded from further investigations.

Table 6.1: Factors of vulnerability and explaining indicators

Factor	Indicator
Social vulnerability factors	
individual's characteristics	
age	percent of population under 5 and above 65; median age
gender	gender per percentage of total population
population	
population density	number of housing units per square mile, total human population density (persons / km^2)
population growth	birth rate (number of birth per 1000 population)
education	
education	education expenditure as % of GNP
employment	
employment	% unemployed; percent of population participating in the labour force
health	
access to medical services	number of physicians per 1000 population
Economic vulnerability factors	
(socio) economic status	
economic capacity	GDP per capita (current US$)
size of domestic market / resource base	
small size	population, land area; gross national product (GNI)
technology / research	
research and development	R&D investment (% GDP); researchers in R&D per million population
infrastructure / access to resources	
transport network	roadways; waterways; railways [in km]
infrastructure / accessibility	access to electricity; access to improved sanitation facilities; access to improved water source (for all 3: % total population)
economy	
type of economic activities	%age of arable land, arable land (in hectares); %age of urban / rural population
dependence on primary commodities	agriculture (% of GDP)
health	
health expenditures	public expenditure on health as per cent of GDP
dependence	
export concentration	exports of goods and services (% of GDP)

dependence on strategic imports	imports of goods and services (% of GDP); energy imports, net (% of energy use); food imports (% of merchandise imports); ores and metals imports (% of merchandise imports)
Physical vulnerability factors	
infrastructure	
public infrastructure	road density (km of road per 100 km^2 of land area)
population	
population density	residents / km^2
urbanization	percent rural / urban population
location	
location of dwelling	(urban/ rural) population living in areas where elevation is below 5m (for all 3: % of total population)
Environmental vulnerability factors	
land use / land cover	
ecology	terrestrial / marine protected areas (% of total area); forest area / arable land (% of land area)
population	
social pressure	total human population density
degradation	
country wide / regional environmental degradation	agricultural irrigated land (% of total agricultural land)
regions characteristics	
lowlands	(urban / rural) land area where elevation is below 5 meters rural land area where elevation is below 5 meters (for all 3: % of total land area)
borders	number and length of land and sea borders shared with other countries
country dispersion	ratio of length of borders (land and maritime) to total land area
land area	total land area (km^2)
coasts	km of coastline (scale by land area)

6.4 Step 3 - Relation between business closure times and vulnerability factors

As can be seen in figure 6.3, the mean closure times for the investigated countries and natural disaster types are varied. To explain those differences

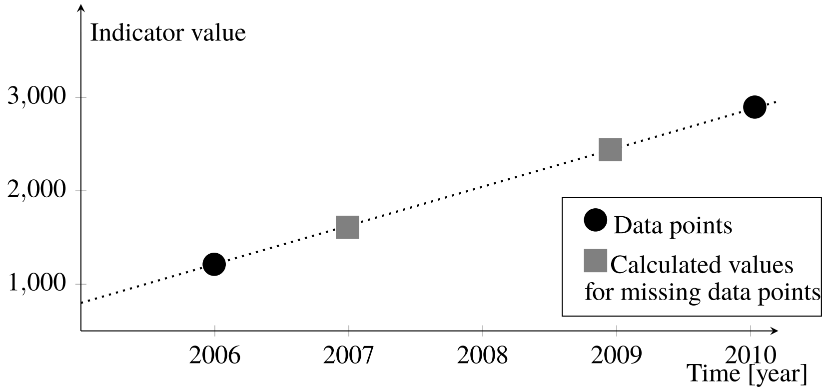


Figure 6.4: Linear interpolation for missing data points

a linear regression is used, testing the relation between mean closure times and factors of place vulnerability (out of step 2). The dependent variable $Y = mean\ closure\ time\ (MCT)$ is thereby explained through one or more explanatory variable(s) X - the vulnerability factors and their related indicators.

First a simple linear regression was computed, so a single vulnerability indicator X and an absolute term β_0 explains the mean closure time Y. The values x_i, y_i for $i = 1, ..., n$ are displayed through a linear model, where the x_i are non stochastic and y_i realizations of stochastic variables Y_i (here and following ([146], p.155ff).

$$\begin{aligned} Y_i &= \beta_0 + \beta_1 X_i + U_i \qquad\qquad i = 1, ..., n \\ \beta_0, \beta_1 &\in \mathbb{R} \end{aligned} \tag{6.6}$$

The $x_1, ..., x_n$ are known and fixed (non stochastic) values, given that all x_i are non-identical. For the error variable U_i applies:

$$\begin{aligned} \mathbb{E}[U_i] &= 0 \\ \mathrm{Var}[U_i] &= \sigma^2 \text{ with } 0 < \sigma^2 < \infty \qquad\qquad i = 1, ..., n \\ U_1, ..., U_n & \text{ are not correlated} \end{aligned} \tag{6.7}$$

The simple linear regression enabled a first glimpse on the relation between mean closure times and a single indicator, but it is expected that more than one indicator is needed to explain the connection. This is supported by the statements already made in previous chapters, where for a holistic vulnerability assessment, factors from different categories must be considered (social, economic, physical and environmental). Therefore also multiple linear regression models are tested.

Within the multiple linear regression with K non stochastic explanatory variables, the observed values $(x_{i1},...,x_{iK},y_i)$ for $i = 1,...,n$ are described by a linear model with all x_{ij} being non stochastic, while all y_i are realizations of a random variable Y_i with
$\beta_0, \beta_1, ..., \beta_K \in \mathbb{R}$ (here and following [146], p.161). All x_{ij} for $i = 1,...,n$ and $j = 1,...,K$ are known and fixed, so that the following equation applies:

$$Y_i = \beta_0 + \beta_1 X_{i1} + ... + \beta_K X_{iK} + U_i \qquad i = 1,...,n \qquad (6.8)$$

For the error variable U_i the above remarks from equation 6.7 are still valid.

For the selection of potential explanatory variables the following 4 groups were chosen and analyzed:

- a combination of the best simple linear regression results
- a combination of four indicators (one out of each category)
- a combination of four indicators from the same vulnerability factor/category
- four indicators as a result of a totally free combination out of all indicators

At last the aggregation of four values was chosen, because the regression with one indicator out of each category (what is recommended based on the remarks already made) requires a minimum of four values. That is why, less than four indicators are not tested nor more than four to avoid overfitting of the underlying regression model. The statistics degree of freedom is therewith 16. To automate the model fit and due to the complexity with more than 3500 single data points a Python script was written and applied ([303]). Figure 6.5 show exemplary the results calculated with the Python script.

The final selection of a regression model is based on the goodness of fit, focusing on the coefficient of determination R^2 and an appropriate condition

```
                          OLS Regression Results
==============================================================================
Dep. Variable:                Lottery   R-squared:                       0.348
Model:                            OLS   Adj. R-squared:                  0.333
Method:                 Least Squares   F-statistic:                     22.20
Date:                Mon, 14 May 2018   Prob (F-statistic):           1.90e-08
Time:                        21:48:09   Log-Likelihood:                -379.82
No. Observations:                  86   AIC:                             765.6
Df Residuals:                      83   BIC:                             773.0
Df Model:                           2
Covariance Type:            nonrobust
===================================================================================
                      coef    std err          t      P>|t|      [0.025      0.975]
-----------------------------------------------------------------------------------
Intercept         246.4341     35.233      6.995      0.000     176.358     316.510
Literacy           -0.4889      0.128     -3.832      0.000      -0.743      -0.235
np.log(Pop1831)   -31.3114      5.977     -5.239      0.000     -43.199     -19.424
==============================================================================
Omnibus:                        3.713   Durbin-Watson:                   2.019
Prob(Omnibus):                  0.156   Jarque-Bera (JB):                3.394
Skew:                          -0.487   Prob(JB):                        0.183
Kurtosis:                       3.003   Cond. No.                         702.
==============================================================================

Warnings:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.
```

Figure 6.5: Output of multiple linear regression

number (which 'measures the sensitivity of the estimates to changes in X' (here and following ([18], p.86)). 'A large condition number indicates that small changes in X can cause large changes in the estimated coefficients'. 'Generally, if the condition number is less than 100, there is no serious problem with multicollinearity. Condition numbers between 100 and 1000 imply moderate to strong collinearity, and if [...] [it] exceeds 1000, severe multicollinearity is indicated' ([188], p.298).

6.5 Step 4 - Frequency of natural disaster

Following the already made remarks on the LDA apart from the severity of events a frequency distribution is also necessary, which is calculated, using historical data for the countries and event types mentioned in table 6.2.

Table 6.2: Natural disaster types considered for the different regions

Region	Event type
USA	Earthquake, Hurricane, Flood
New Zealand	Earthquake
Germany	Flood
Pakistan	Flood
Thailand	Flood
Australia	Flood, Cyclone
Canada	Flood
South Africa	Flood

'The frequency N_T with a probability function p_N explains [thereby] the distribution of the number of events within a specific time interval T ([292], p.50)'.

As N_T can only be an integer value, the modeling with a discrete distribution is recommended, whereby possible distributions can be: Poisson, Exponential, Gamma, Binomial, Negative binomial and Panjer ([292], p.50; [62], p.48ff). Whereby 'the chosen distribution needs to be the distribution that gives the closest approximation to the observed data' ([144], p.73). The suitability of a distribution can be evaluated taking the following aspects into consideration ([144], p.73ff):

- upper bound of the distribution
- upper tail of the distribution
- shape of the body of the distribution
- lower tail of the distribution
- lower bound of the distribution
- exact zero values

For the analysis of natural disasters especially the tail of a distribution is of interest, thus it is expected that this aspect has a high influence on the choice of a distribution in those cases. If a frequency distribution for future time intervals is modeled in dependence to the already realized loss events, a counting process can be introduced, which allows to consider the progression of loss events and not only the very number within a given time interval ([62], p.48ff). Within the high range of possible processes especially the Poisson process is used to describe highly random behavior ([164], p.1; [43], p.5), like natural disasters. Additionally the Poisson process is seen as a standard ([2], p.7) and it is also one of the simplest time-continuous processes ([377], p.61) to apply. An easy application is necessary particularly for the acceptance and comprehensibility in an applying corporation. Therefore the Poisson process is used and also described here.

The counting process $N(t), t \geq 0$ is a homogeneous Poisson Process (HPP), if the following requirements apply (here and following ([2], p.8); ([62], p.60)):

$$N(0) = 0 \tag{6.9}$$

$$N(t) \text{ has independent increments (about disjoint time intervals)} \tag{6.10}$$

$$\text{For all } t > 0 \text{ applies } 0 < P(N(t) > 0) < 1 \tag{6.11}$$

$$N(t+u) - N(t) \sim \mathbf{Pois}(\lambda u) \text{ for any } t \geq 0,\ u > 0 \tag{6.12}$$

$$\text{The random variables } N(t_{i+1}) - N(t_i), i = 0, ..., n-1 \tag{6.13}$$
$$\text{are for any } 0 = t_0 < t_1 < ... < t_n \text{ independent of each other}$$

$\mathbf{Pois}(\alpha)$ expresses the Poisson distribution with parameter α, which means with $\alpha = \lambda u$, where λ presents the expected number of losses within the time interval $[0, u]$, apply:

$$P(N(u) = n) =: p_n(u) = \frac{(\lambda u)^n}{n!} \cdot e^{-\lambda u} \tag{6.14}$$
$$\text{for } n \in \mathbb{N} \text{ and } u > 0$$

$$\mathbb{E}[N(u)] = \text{Var}[N(u)] = \lambda u \tag{6.15}$$

Based on this mathematical formulation the written Python Script (see figure 6.6) computes the frequency for all given events as difference between two successive events (in days) and draws the related histogram, like the exemplary one in figure 6.7.

```
def create_frequency_plot(country):
    dates = df[df['Country']==country].sort_values(by='Began')['Began']
    y = (dates.diff(1)).apply(lambda x: x.total_seconds()/(24*60*60))

    y.hist(bins=100)
    plt.title(country)
    plt.show()

    ax = seaborn.distplot(y.values[1:], bins=100, norm_hist=True)
    plt.title(country)
    plt.show()
```

Figure 6.6: Python script to create a frequency plot

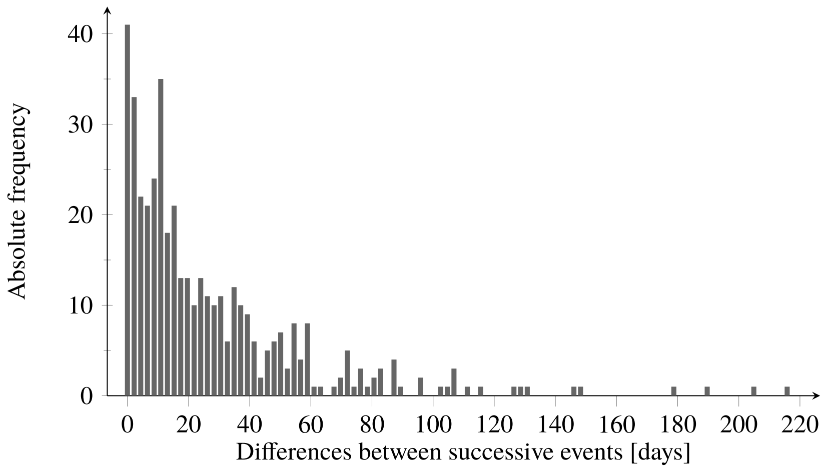


Figure 6.7: Empirical distribution of differences between successive events for USA

6.6 Step 5 - Compound distribution

The compound distribution (as the next step of the LDA) is now calculated as the combination of the severity distribution from step 1 and the frequency distribution out of step 4, giving the total loss distribution for a specific time interval T ([292]). The process is graphically illustrated in figure 6.8 and mathematically described below.

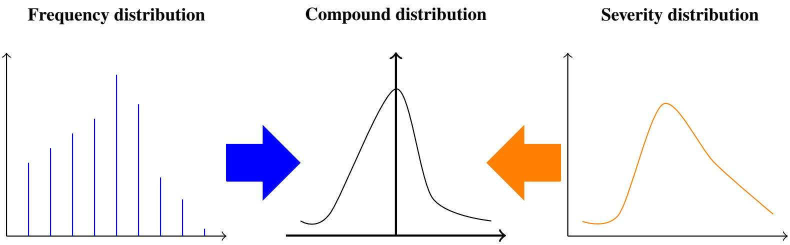


Figure 6.8: Compound distribution (based on [3], p.286)

The convolution $(f * g)(x)$ of two ordinary functions $f(x)$ and $g(x)$ in $\mathbb{R}^n$ is a function defined through the following integral (taken from [147], p.300):

$$(f * g)(x) = \int_{\mathbb{R}^n} f(y)g(x-y)dy \tag{6.16}$$

Whereby for both functions apply, that the respective random variables are stochastically independent. That means the severity (the extent of impact) has no influence on the probability (frequency) and vise versa. The cumulative loss $L(t)$ within a time interval $[0,t]$ can be expressed as an accumulated claim process ([2], p.4f), which can be seen in figure 6.9.

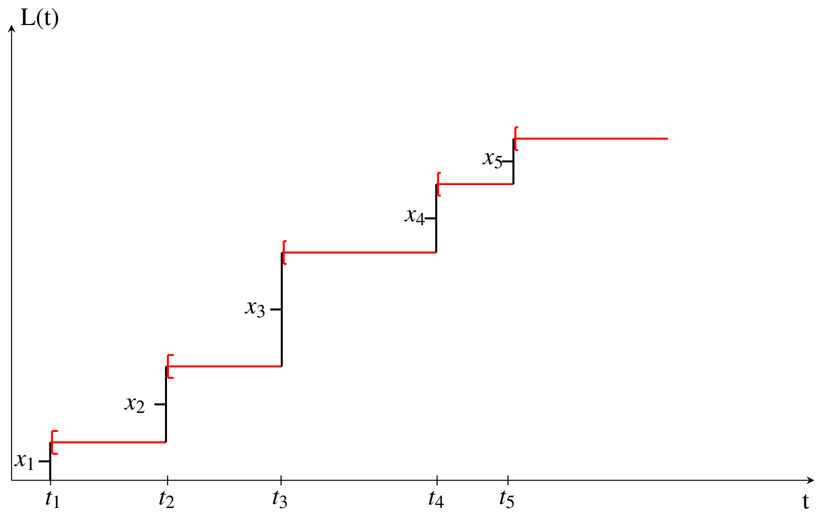


Figure 6.9: Accumulated claim process ([2], p.5)

'The random variables X_1, X_2, ... , X_n correspond the extent of loss (per loss event), [while] $X_i > 0$ quantifies the extent of the i-th loss event' ([2], p.5). With $N(t)$ as counting process (see step 4), which refers to the number of losses within the time interval $[0,t]$, applies (here and following [2], p.4ff):

$$L(t) = \sum_{i=1}^{N(t)} X_i \tag{6.17}$$

$$\text{with } L(t) = 0 \text{ for } N(t) = 0 \tag{6.18}$$

'As $N(t)$ is a homogeneous Poisson Process (HPP), $L(t)$ is a compound Poisson process (CPP)', and it applies:

$$\mathbb{E}[L(t)] = \mathbb{E}[N(t)]\mathbb{E}[X] \tag{6.19}$$

$$\text{Var}[L(t)] = \mathbb{E}[N(t)]\text{Var}[X] + \mathbb{E}[X]^2\text{Var}[N(t)] \tag{6.20}$$

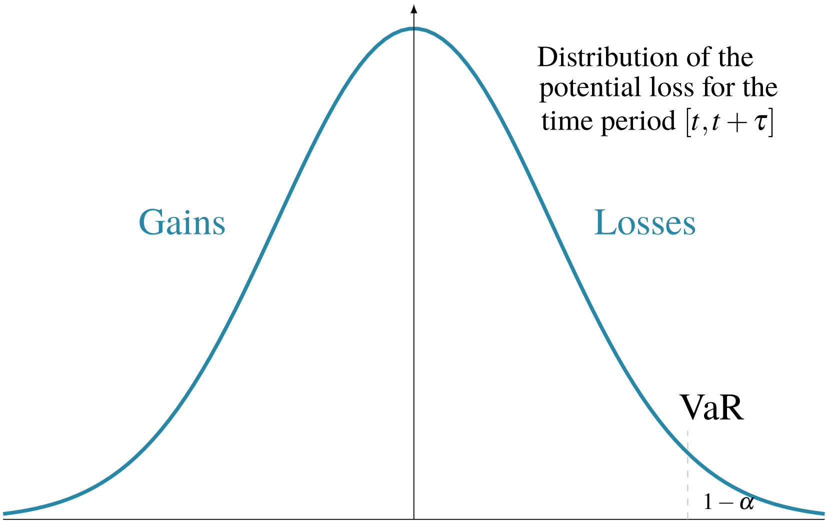


Figure 6.10: Loss distribution and Value at risk (taken from [110], p.3)

With F^{n*} as n-th convolution of the distribution function F, it applies for the distribution function $G_t(x)$:

$$G_t(x) = P(L(t) \leq x) = \sum_{n=0}^{\infty} P(N(t) = n)P(L(t) \leq x | N(t) = n) \tag{6.21}$$

$$= \sum_{n=0}^{\infty} P_n(t)F^{n*}(x) \text{ with } x \geq 0,\ t \geq 0 \tag{6.22}$$

'Of particular interest [for the Loss Distribution Approach] are the (1 - α)-quantiles $Q_{1-\alpha}[L(t)] = G_t^{-1}(1-\alpha)$ for the given confidence levels $0 < \alpha < 1$[...] α, as they correspond the Value at Risk of the compound distribution with a confidence level α (for the regarded period $[0,t]$)' ([2], p.17). [1] The graphical illustration can be found in figure 6.10.

In the context of this work the VaR (Value at risk) states the delivery time at risk from natural disasters. Below is the approach presented within a case study.

[1] The term $L(t)$ is equivalent to $S(t)$, which is used in the literature source. Due to notations this term was changed in this work.

7 Application SCperformND approach

7.1 Vulnerability indicators with highest relevance to explain delivery time deviations

Following the steps (here **step 1**) introduced in the previous chapter, first the business closure times were extracted from the 32 studies identified within the literature review. The complete overview on the data set can, as said, be found in appendix A.8. Due to a lack of space and for reasons of comprehensibility only just an excerpt of the complete table (see table 7.1) is shown and explained ([382]; [379]).

Table 7.1: Business closure times

ID (literature)	**Event-ID**	**% businesses closed within interval**	**Left-bound [days]**	**Right-bound [days]**	**Mean closure time**
1	1	0.245	0	0	0
1	1	0.446	0.042	3	0.019
1	1	0.195	4	7	0.78
1	1	0.074	8	21	0.592
1	1	0.04	22	inf	14.6
2	1	0.249	0	0	0
2	1	0.751	8	8	6.008

For easier computability for each given disaster a so called event-ID (k) is introduced, which is number 1 in table 7.1. That event-ID refers to the Loma-Prieta Earthquake, which hit California in 1989. The complete overview on events and their associated event-ID is given in table 7.2. Additionally the literature sources are classified with ID, which was necessary as sometimes more than one author investigated the same event. The results Webb et al. 2002 ([382]) (ID 1) revealed on business closure are, that of the 910 survey respondents, 24,5% (stated as 0,245 in table 7.1) did not close. Therefore the interval span is 0, as well as the mean closure time. The following row shows that 44,6% closed for one hour (left-bound) up to 3 days (right-bound). One hour is $\frac{1}{24}day = 0,042$, as all values are stated in days[1]. The values can of course also be converted to other units, like hours, if needed. It must only be ensured that all values have the same unit.

Table 7.2: Natural disaster events

Event-ID	Region	Sub-region	Event type	Event name	Event year
1	USA	California	Earthquake	Loma-Prieta Earthquake	1989
2	USA	Florida	Hurricane	Hurricane Andrew	1992
3	New Zealand	Canterbury region	Earthquake	Canterbury / Darfield Earthquake	2010
4	USA	Florida	Hurricane	Hurricane Wilma	2005
5	USA	Washington	Earthquake	Nisqually Earthquake	2001
6	Germany	Saxony	Flood	Germany flood 2002	2002
7	USA	Louisiana, Mississippi	Hurricane	Hurricane Katrina	2005
8	USA	Iowa	Flood	Midwest floods 1993	1993
9	New Zealand	Gisborne region	Earthquake	Gisborne Earthquake	2007
10	USA	California	Earthquake	Northridge Earthquake	1994
11	Pakistan	Khyber Pakhtunkhwa, Punjab and Sindh Provinces	Flood	Pakistan flood 2010	2010
12	Thailand	Pathumthani province	Flood	Thailand flood 2011	2011
13	Australia	Queensland	Flood	Queensland flood 2010	2010

[1] Sources that used another time resolution had been converted to days.

14	Australia	Queensland	Flood and Cyclone	Queensland flood and Cyclone Yasi	2010 /2011
15	USA	North Carolina	Hurricane	Hurricane Berta	1996
16	USA	North Carolina	Hurricane	Hurricane Fran	1996
17	USA	North Carolina	Hurricane	Hurricane Bonnie	1998
18	Germany	Saxony, Bavaria, Thuringia, Saxony-Anhalt, Brandenburg, Schleswig Holstein, Lower Saxony, Baden-Wuerttemberg, Rhineland Palatinate	Flood	Germany flood 2013	2013
19	United Kingdom	Isle of Portland	Flood	UK flood 1978-79	1978 /1979
20	Canada	Calgary	Flood	Canada flood 2013	2013
21	South Africa	Industrial Complex Vereeniging	Flood	South Africa flood 1993	1993

To gain the mean closure time (the expected value of the distribution) for each row, the left-bound is multiplied with % businesses closed within interval.

$$MCT_{row} = \text{\% businesses closed within intervall}_{row} \cdot \text{left-bound [days]}_{row} \quad (7.1)$$

Within the example for the second row the MCT is: $0.019 = 0.446 \cdot 0.042$. If the closure time was stated as *inf*, referring to a business that closed forever and no information about the point in time when that happened was made, it is assumed that the final closure took place after one year. In those cases the left-bound is multiplied with 365. The interval center was tested for calculation too, but resulted in approximately the same values, that is why the left-bound was kept. The sum over the last column for each ID gives the mean closure time for each literature source and the investigated region. For the given ID 1, the MCT is around 16 days. As already mentioned, sometimes more than one author investigated the same event, in these cases the mean closure times are averaged over the event-ID, providing the mean time the businesses were closed during / after the Loma-Prieta earthquake of 1989 here.

Let k be the k-th event with Event-ID k and n the number of data sources investigating the closure times for the event with Event-ID k. The MCT for Event-ID k is stated as follows:

$$MCT_k = \frac{1}{n}\sum_{i=1}^{n} \mathrm{MCT}_i = \frac{1}{n}\sum_{i=1}^{n}\sum_{row=ID} \mathrm{MCT}_{row} \tag{7.2}$$

For event-ID 1 the MCT is:

$$MCT_1 = \frac{1}{2}\Big(\big(0+0.019+0.78+0.592+14.6\big)+\big(0+6.008\big)\Big) = 11 \text{ days} \tag{7.3}$$

The MCT for all events is graphically illustrated in figure 6.3 in chapter 6.2.

Within **step 2** are the vulnerability indicators identified which shall be part of the analysis. These are (in this work) the ones already mentioned in table 6.1 in chapter 6.3. Depending on the context of analysis it is also possible to exclude or include other indicators. As stated earlier those in table 6.1 are the ones the majority of authors mentioned and those that fitted the topic of this work best. So here is the complete set of indicators from table 6.1 tested within **step 3** - the relation between business closure times and vulnerability indicators. Therefore the indicators from the respective event year and the MCTs were condensed within a table, of which an extract can be seen in table 7.3. To prevent negative results the values are logarithmized.

To identify the vulnerability indicators with the greatest influence on business closure several linear regression models were tested. The comparison between all tested regressions revealed that the regression selecting one indicator out of each category has the best 'combination' of a high coefficient of determination R^2, with condition numbers that are better than in the other cases. Even though the condition numbers are in any tested case higher than recommended (the problem can be explained out of the relatively few data sets), this regression model shows the best results. With a coefficient of determination R^2 of 0.575 the 4 indicators in table 7.4, which are also pictured in the extract of the Python Script in figure 7.1, show the greatest impact on business closure times respectively delivery time deviations. To repeat, the equation in 7.4 explains

Table 7.3: Extract of data for regression

Region	**Event year**	**Event type**	**birth rate (number of birth per 1000 population)**	**forest area (% of land area)**	**roadways in km**	**population living in areas where elevation is below 5 meters (% of total population)**
Australia	2010	Flood	13.7	16.04	823,217	4.52
Australia	2011	Flood	13.6	16.08	823,217	4.51
Canada	2013	Flood	10.9	38.18	1,304,066	2.26
Germany	2002	Flood	8.7	32.58	231,600	4.04
Germany	2013	Flood	8.3	32.75	230,400	4.04
New Zealand	2007	Earthquake	15.15	38.62	92,931	4.23
New Zealand	2010	Earthquake	14	38.55	833,293	4.23
Pakistan	2010	Flood	30.17	2.19	255,534	1.06
South Africa	1993	Flood	27.16	7.62	186,038	0.16
Thailand	2011	Flood	11.51	31,86	146,490	10.34
USA	1989	Earthquake	16.4	33.02	6,238,624	2.57
USA	1992	Hurricane	15.8	33.05	6,279,186	2.55
USA	1993	Flood	15.8	33.05	6,284,024	2.55
USA	1994	Earthquake	15	33.07	6,286,958	2.55
USA	1996	Hurricane	14.4	33.09	6,307,728	2.54
USA	1998	Hurricane	14.3	33.12	6,286,552	2.54
USA	2001	Earthquake	14.1	33.16	6,354,213	2.50
USA	2005	Hurricane	14	33.26	6,430,335	2.51

Table 7.4: Regression coefficients

Regression coefficient	Indicator	Indicator name
3.2432	x_1	birth rate (number of birth per 1000 population)
0.7483	x_2	forest are (% of land area)
-0.5717	x_3	roadways in km
0.1306	x_4	population living in areas where elevation is below 5 meters (% of total population)

once more the calculation of the MCT. The terms β stand for the respective values of the regression which are multiplied with the indicator values x.

$$y := \ln MCT = \beta_1 \ln x_1 + \beta_2 \ln x_2 + \beta_3 \ln x_3 + \beta_4 \ln x_4 \tag{7.4}$$

$$MCT = e^y = e^{\beta_1 \ln x_1 + \beta_2 \ln x_2 + \beta_3 \ln x_3 + \beta_4 \ln x_4} \tag{7.5}$$

$$MCT = e^{\beta_1 \ln x_1} \cdot e^{\beta_2 \ln x_2} \cdot e^{\beta_3 \ln x_3} \cdot e^{\beta_4 \ln x_4} \tag{7.6}$$

$$MCT = x_1^{\beta_1} \cdot x_2^{\beta_2} \cdot x_3^{\beta_3} \cdot x_4^{\beta_4} \tag{7.7}$$

A high birth rate (indicator x_1) indicates high population growth, which 'focuses on the potential for damage relating to expanding human populations. It signals increasing rates of habitat damage, exploitation of natural resources and disposal of wastes [...]' (here and following [100]). 'The greater numbers of people increases pressure on the environment' and enhances the vulnerability of people and businesses. Other challenges related to large population growth are that housing often lack quality, that 'social services networks may not have had time to adjust to increased populations' ([67], p.248) and that it can 'result in a lack of infrastructure and therefore of disaster management capacity' ([237], p.94).

The second variable x_2 is referring to forest areas, focusing on 'the loss of natural vegetation cover in a country' (here and following [100]). 'By affecting people's livelihood, environmental degradation increases the vulnerability of some communities and can also contribute to increasing the vulnerability of others through migrations' ([229], p.124). 'The existing level of environmental degradation is of particular relevance for evaluating the vulnerability [e.g.] of

['birth rate (number of birth per 1000 population)', 'forest area (% of land area)‘, 'roadways in km‘, 'population living in areas where elevation is below 5 meters (% of total population)‘]

NumObs: 18
NumVar: 4
AIC 61.69182948111878
BIC 65.25331651270344
RSquared 0.9030003875332373
RSquared_adj 0.8752862125427336
F_Value 32.58261838364858
F_Value prob 5.915079172866626e-07
Log_Likelihood -26.84591474055939

Parameter:
coef 3.243193, 0.748289, -0.571718, 0.130556
coef std err 0.794136, 0.569588, 0.222917, 0.451225
t values 4.083928, 1.313738, -2.564713, 0.289336
P>|t| 0.001117, 0.210056, 0.022467, 0.776565
Conf Interval 1.539941, 4.946445, -0.473355, 1.969933, -1.049828, -0.093609, -0.837227, 1.098338

Cond_No 43.86941418941537

Fitted Values
[2.9747890722910872, 2.9526083703419697, 2.528714681398328, 2.742931509476166, 2.5972431072921554, 5.197300832949228, 3.685690483794556, 4.524787083181398, 5.051748251519895, 4.018586016562126, 2.8672305727435092, 2.7421694931278537, 2.741660698105995, 2.57316636524602, 2.43910542645046, 2.4

Figure 7.1: Regression results case study

floods, droughts and cyclones. The effects of environmental degradation might vary with climate conditions and affect areas differently [...]' ([237], p.96). But deforestation in general 'leads to soil erosion, loss of nutrients and marginality of agriculture' and 'can lead [...] [to] new pattern of flood, drought, fire or landslide hazards' ([333], p.5). 'Areas of natural vegetation are viewed as refuges [...]. Natural forests and vegetated areas are also likely to be important areas for groundwater intake, soil production, CO_2 - oxygen relationships and attenuating air and water pollution. A country's resilience to future hazards will be related to this rate.

The road network (indicator x_3) is part of the 'institutional infrastructure [that] provide[s] the framework for disaster mitigation, preparedness and response activities' ([237], 88ff). 'Loss of sewers, bridges, water communications, and transportation infrastructure compounds potential disaster losses. The loss of infrastructure may place an insurmountable financial burden on smaller communities that lack the financial resources to rebuild' ([67], p.247). The larger the transport network the easier corporations can also reroute if a certain area is affected through natural disasters.

The fourth variable x_4 is the population living in areas where elevation is below 5 meters (as % of total population). The elevation influences the vulnerability to floods and cyclones strongly ([237], p.91ff), as 'areas of lowlands are those that will tend to be the first to flood' ([100]). The relevance of this indicator might stem from the fact that the majority of data sources investigated floods. The higher the percentage of population living in areas under 5 meters (per cent), the higher their vulnerability. The high susceptibility of those areas is also related to the fact that coastal regions (which are often areas of lower elevation) are the most productive living areas of a country ([100]), and because of that also the most densely populated ones ([102], p.1590; [213], p.1390). This results also in a high concentration 'of residential housing, transport and energy supply infrastructure' ([80], p.478) and also in a high amount of businesses located. Moreover coasts are often popular tourist areas and an important asset of economic activity ([213], p.1390). Thus due to their specific location, rapid urbanization and high concentration of assets those areas are highly vulnerable to natural disasters ([296], p.1) and with it the population and businesses located.

Coming up next are the results of SCperformND compared to the observed data from the literature studies.

Model validation

To validate the model a in sample validation was done, testing the fit between the observed closure times and the closure times calculated with SCperfomND on the basis of the four indicators identified above. The literature values as well as the calculated values of the MCTs can be found in table 7.5 and are graphically illustrated in figure 7.2.

In a perfect model all data points lie directly on the orange line through the point of origin, the further a data point is away from this line the larger the respective model error.

Table 7.5: Model validation

Region	**Event year**	**MCT from literature**	**MCT from SCperformND**
Australia	2010	22.74	19.59
Australia	2011	15.61	19.16
Canada	2013	7.36	12.54
Germany	2002	27.85	15.53

Germany	2013	13.38	13.43
New Zealand	2007	237.43	180.78
New Zealand	2010	10.81	39.87
Pakistan	2010	87.40	92.28
South Africa	1993	182.5	156.30
Thailand	2011	82.57	55.62
USA	1989	11	17.59
USA	1992	93.87	15.52
USA	1993	1.23	15.51
USA	1994	77.29	13.11
USA	1996	6.60	11.46
USA	1998	3.06	11.23
USA	2001	12.37	10.65
USA	2005	60	10.37

$$\frac{\partial MCT}{\partial x_1} = \beta_1 x_1^{\beta_1 - 1} \cdot x_2^{\beta_2} \cdot x_3^{\beta_3} \cdot x_4^{\beta_4} = 0.006412 \cdot x_1^{2.243193} = 1.85 \quad \text{for} \quad x_1 = 12.5 \tag{7.8}$$

$$\frac{\partial MCT}{\partial x_2} = x_1^{\beta_1} \cdot \beta_2 x_2^{\beta_2 - 1} \cdot x_3^{\beta_3} \cdot x_4^{\beta_4} = 0.382412 \cdot x_2^{-0.251711} = 0.1575 \quad \text{for} \quad x_2 = 33.9 \tag{7.9}$$

$$\frac{\partial MCT}{\partial x_3} = x_1^{\beta_1} \cdot x_2^{\beta_2} \cdot \beta_3 x_3^{\beta_3 - 1} \cdot x_4^{\beta_4} = -32500 \cdot x_3^{-1.571718} = -6.123 \cdot 10^{-7} \quad \text{for} \quad x_3 = 6662841.41 \tag{7.10}$$

$$\frac{\partial MCT}{\partial x_4} = x_1^{\beta_1} \cdot x_2^{\beta_2} \cdot x_3^{\beta_3} \cdot \beta_4 x_4^{\beta_4 - 1} = 0.826248 \cdot x_4^{-0.869444} = 0.3712 \quad \text{for} \quad x_4 = 2.51 \tag{7.11}$$

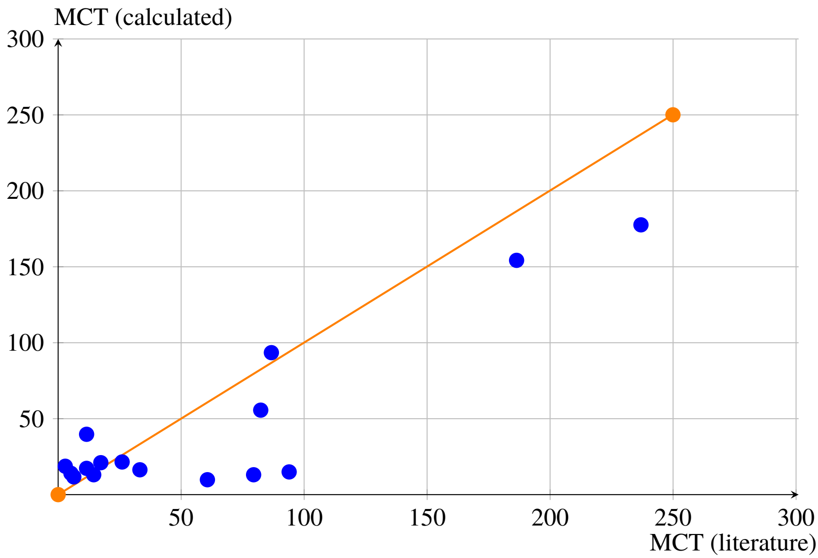


Figure 7.2: Model validation

For the observed closure times the overall MCT is 52.95 days in the mean per event, while SCperfomND calculates 39.47 days. The mean error, defined as difference between mean closure time from SCperformND and the observed closure time is therefore -13.48 days and the mean absolute error 22.02 days. The deviations between all calculated and observed values can also be seen in figure 7.3.

Additionally a sensitivity analysis is done, testing the change of the MCTs when the underlying vulnerability indicator is changed infinitesimal. Therefore each of the four indicators was tested for the influence a change will bring on MCT, while all other indicators remain steady. The partial derivations 7.8 to 7.11 for x_1, x_2, x_3 *and* x_4 form the analytical basis for the plots in figures 7.4 to 7.7. When the rate of birth (per 1000 population) changes one percent the MCT changes about 1.85 days (see figure 7.7 and equation 7.8). This indicator shows also the greatest influence on business closure in comparison the other three used within this work. From the figure and mathematics it can also be derived that a change of forest area per one percent results in a change of MCT by 0.16 days. While the influence of the road network change is $-6.123 \cdot 10^{-7}$

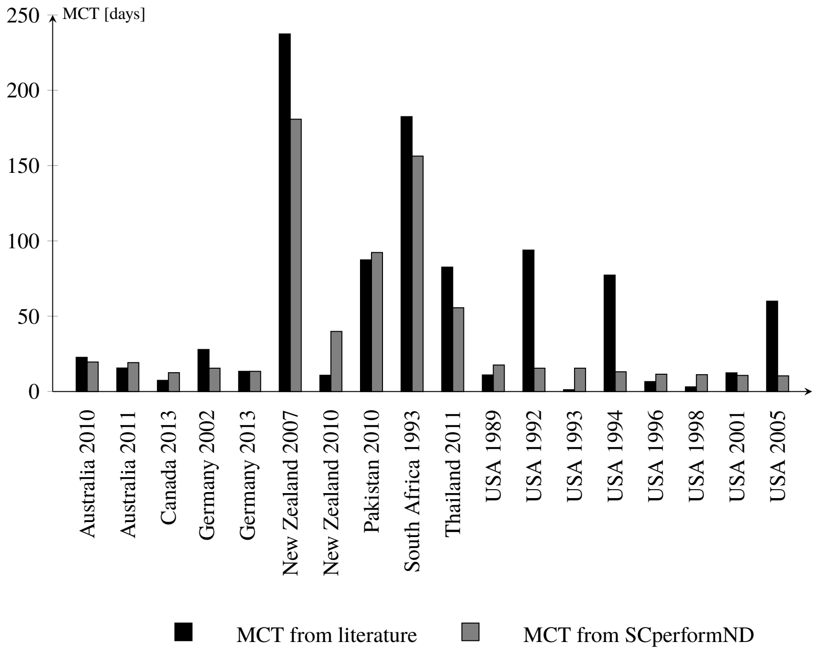


Figure 7.3: Comparison MCT from literature and SCperformND

on MCT and the percentage of people living in areas where elevation is below 5 meters has an influence of 0.37 days when changed for one per cent.

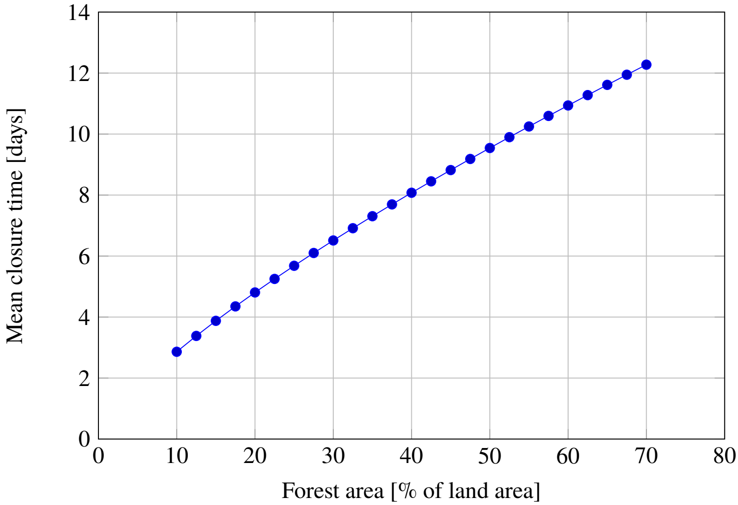


Figure 7.5: Sensitivity analysis forest area (% of land area)

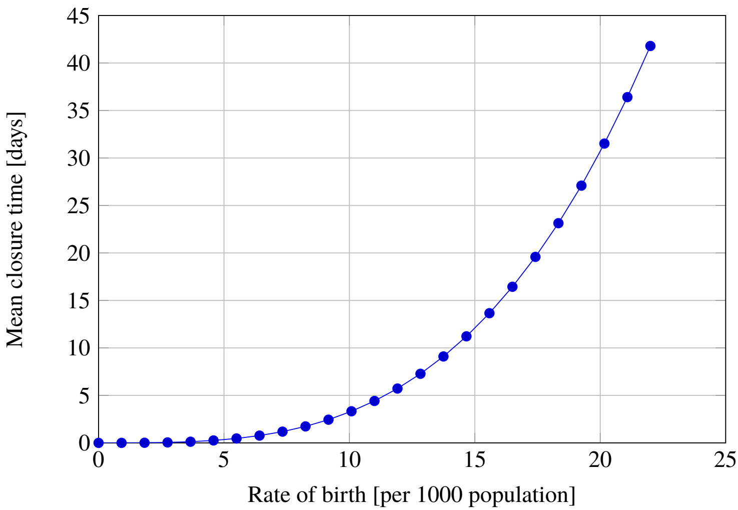


Figure 7.4: Sensitivity analysis Rate of birth (per 1000 population)

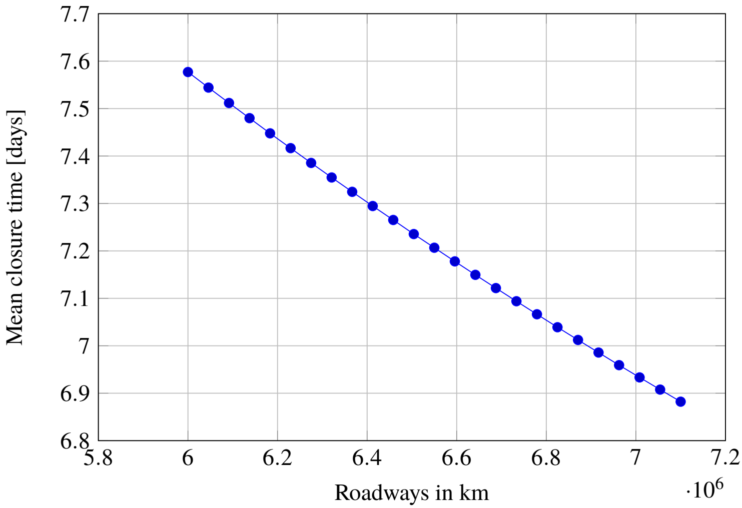


Figure 7.6: Sensitivity analysis roadways in km

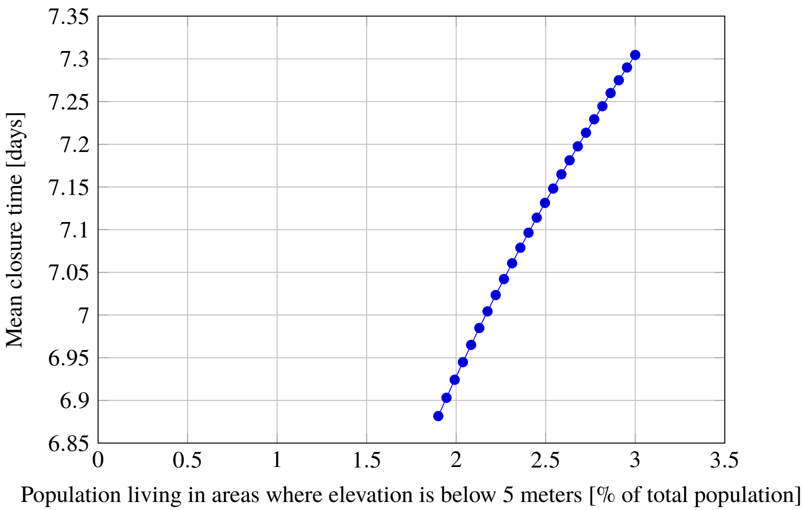


Figure 7.7: Sensitivity analysis Population living in areas where elevation is below 5 meters (% of total population)

Below are now the identified indicators used within the application of SCperformND for a concrete sample region.

7.2 Case study - United States of America

In the previous chapter the indicators with the highest influence on business closure times had been identified. This section aims to present the SCperfomND approach for a sample region - the United States of America (USA). This explanatory location has been chosen, as the majority of sources (out of the 32 studies mentioned) investigated the USA, consequently the available data basis is broader than for the other regions (Germany, Canada, Australia, Thailand, Pakistan and South Africa). Following the introduced methodological sequence (see chapter 6) the first part is determined through the identification of business closure times. The indicators with the greatest impact on business closure times had been identified in chapter 7.1, are now for the calculation of a severity distribution (here the MCT) the four indicators: birth rate (number of birth per 1000 population), forest area (% of land area), roadways in kilometer and population living in areas where elevation is below 5 meters (% of total population) used. Different from the calculations already made, for the assessment of future business closure times, the latest values available are now applied. The indicator values can be found in table 7.6 and the respective mean closure time is calculated as follows:

$$\begin{aligned} \ln MCT_{\text{USA}} =& 3.2432 \cdot 2.5257 + 0.7483 \cdot 3.5234 - 0.5717 \cdot 15.7121 + 0.1306 \cdot 0.9203 \\ =& 1.9654940798956 \end{aligned} \tag{7.12}$$

$$MCT_{\text{USA}} = e^{1.9654940798956} = 7.14\ days \tag{7.13}$$

The second step (the identification of vulnerability indicators) and the third step (the relation between business closure times and vulnerability indicators) are already done as the indicators identified as most relevant in chapter 7.1 are utilized. Depending on the research question, the branch or corporate specific requirements can also have other indicators tested within regression, which can result in a different set of explaining indicators.

Table 7.6: Indicators USA

Indicator	**Year**	**Indicator value**	**Indicator name**	**Logarith- mized value**
x_1	2017	12.5	birth rate (number of birth per 1000 population)	2.5257
x_2	2015	33.9	forest area (% of land area)	3.5234
x_3	2016	6,662,841	roadways in km	15.7121
x_4	2010	2.51	population living in areas where elevation is below 5 meters (% of total population)	0.9203

As the USA is the region of interest the frequency of natural disaster in the USA has to be calculated as frequency distribution (step 4). Therefore the sources mentioned in chapter 3.2 were utilized. The respective mathematics can be found in chapter 6.5. Within 33 years (1985-2017)[2] 486 natural disasters occured, of which were 431 floods, 17 hurricanes and 38 earthquakes. This is resulting in an average amount of $14.73 = \frac{486}{33}$ events per year. Moreover, the distribution of the counting process $N(u)$ has to be determined, following the below mentioned mathematics.

$$\lambda u = \frac{K}{N} \tag{7.14}$$

$$\lambda = \frac{K}{Nu} = \frac{K}{U} \tag{7.15}$$

$$U = N \cdot u \tag{7.16}$$

- with $\lambda = 0.04035$ = intensity
- U = 12045 = total length in days
- N = 33 = number of years

[2]This time interval has been chosen as the available information is better in quality and quantity from 1985 on.

- u = 365 = interval length in days per year and
- K = 486 = number of single events

With the average number of events per year with 14.73 and the interval u of 365 days is $\lambda = \frac{14.73}{365} = 0.04035$. The counting process follows therewith a Poisson distribution $Pois(14.73)$. The respective probability mass function is illustrated in figure 7.8.

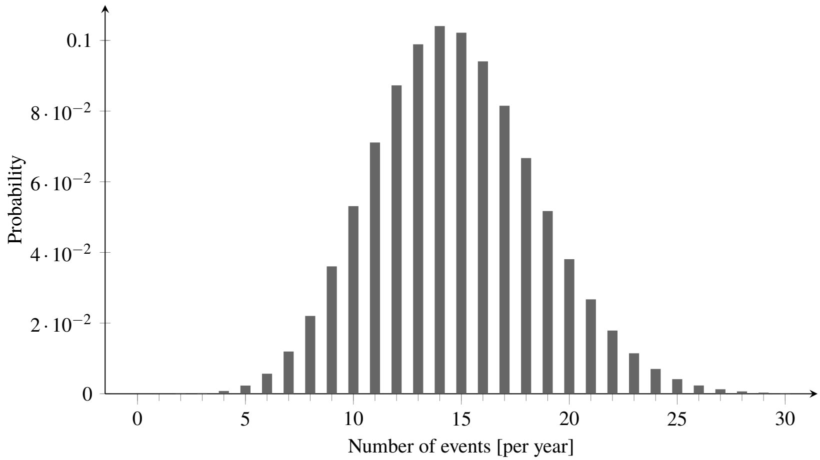


Figure 7.8: Probability mass function for $N(u) = Pois(14.73)$

The cumulative loss $L(t)$ is, as already said in the previous chapter, then expressed as an accumulated claim process (step 5). To repeat:

$$L(t) = \sum_{i=1}^{N(t)} X_i \tag{7.17}$$

$$\text{with } L(t) = 0 \text{ for } N(t) = 0. \tag{7.18}$$

The distribution of X_i (the extent of loss), which is also called the severity distribution was stated as the MCT - which is a single value. Therewith X_i

is a degenerate distribution ([231], p.369) and $L(t)$ is simplified to $L(t) = N(t) \cdot (MCT)$. For the expected value the following applies:

$$\mathbb{E}[L(t)] = \mathbb{E}[N(t) \cdot (MCT)] = (MCT) \cdot \mathbb{E}[N(t)] \tag{7.19}$$

$$\mathbb{E}[N(t)] = \lambda u \tag{7.20}$$

$$\text{with } N(t) \sim \mathbf{Pois}(\lambda u)$$

$L(t)$ follows then $Pois(14.73) \cdot 7.14$, which is illustrated in figure 7.9. The expected value of $L(365) = 105.15$ states that within one year it is expected that a corporation closes for 105.15 days due to a disaster. This value can be perceived as relatively high, but can be based on the fact that the USA were considered as one entity.

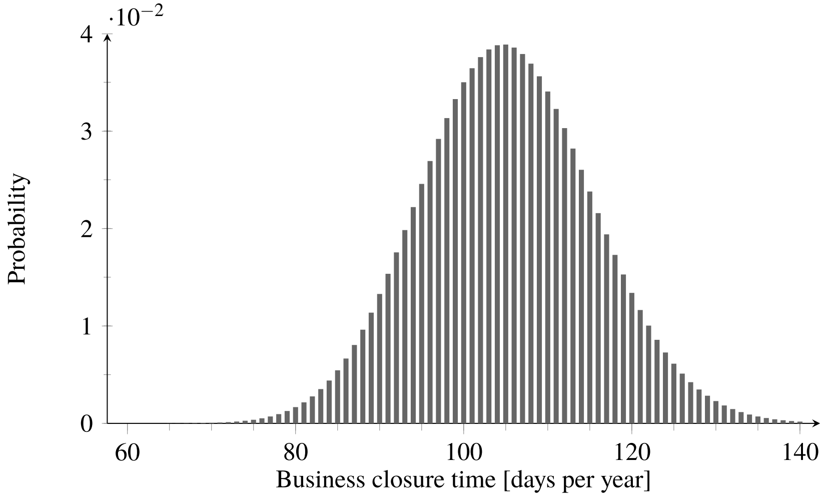


Figure 7.9: Probability mass function for $L(t) = Pois(14.73) \cdot 7.14$

For the 95% quantile, with a confidence level $\alpha = 0.05$ the VaR is

$$Q_{365}^{-1}(0.95) = \ 122 \ days. \tag{7.21}$$

Table 7.7: VaR comparison for sample regions

Country	**MCT per year**	**VaR** (95% quantile, $\alpha = 0.05$)	**VaR** (5% quantile, $\alpha = 0.05$)
Germany	6.74	11	3
Canada	20.60	28	13
South Africa	45.03	56	34
Australia	51.47	61	40
New Zealand	243.37	269	218
Pakistan	61.35	74	49
Thailand	101.58	118	85
USA	105.15	122	89

95% of business closure times are less than 122 days after a disaster. The 5% quantile states that in just 5% of all cases business closure times account for less than 89 days. Coming back to the question of supplier or production location decisions, this value must now be compared to the VaR of all other available alternatives. Therefore the methodology of SCperformND (see chapter 6.1 for repetition of the necessary steps) applied to the other six countries is used within this work. The respective values can be found in table 7.7.

Based on the MCT per year Germany has the lowest value as well as the lowest VaR. Without any further information Germany would therefore be chosen as production or supplier location. The least advantageous country in this example is New Zealand. However it is useful to include additional information, like operational aspects, which were not included in this work due to its context. But for a holistic vulnerability analysis it is necessary to incorporate all aspects that build the potential for harm to a corporation. Moreover it is useful to investigate further smaller areas (like states or communities) for more detailed statements, as indicator values can of course be varied within a country, leading to different MCTs and VaRs. As SCperformND was estimated on country basis, for a deeper analysis data of required granularity would be necessary, which was not available. Nevertheless the functioning of SCperformND was shown and it can easily be applied within a corporation as data on delivery time deviations with respect to business closures are normally tracked on a daily basis. Therewith SCperformND closes the research gap of supply chain risk methods lacking the consideration of natural disasters and the gap of natural disaster assessments lacking the consideration of influences of natural disaster on supply chain performance through a combined approach.

Based on the achievements the work closes with a summary and critical appraisal in the next chapter.

8 Summary and conclusion

8.1 Summary

As can be seen in daily life, the risks of natural disasters are increasing, which is not just demonstrated by the latest global recognized disaster like Hurricane Harvey in 2017. To be competitive, corporations must be aware of those developments and should take the potential risk of natural disasters within supply chain design into consideration from the first day onwards. In the case of strategic decisions, for example supplier selection or location decisions should be evaluated if there is a risk for natural disasters in a specific region. It should always be kept in mind that one disaster strike can easily outweigh the benefits of for example low cost sourcing. So even external shocks are relatively rare in comparison to internal risks, their impact can be much worse. Nevertheless, recent developments have shown that corporations have not jet recognized the importance of that risk category. Most often internal risks are analyzed in detail, while external risks are ignored or even neglected. This is based on the common perception that there is no such urgent need to secure against rarely insecure events, when there are risks with high probabilities. Due to those facts, and the expected increase in frequency and intensity, natural disasters are a growing threat to supply chain resilience. This is analyzed in an intensive literature review, stating factors of increased supply chain vulnerability in chapter 2.

To understand the differences between risk categories, a corporation has to deal firstly with a general classification of supply chain risks as demonstrated in chapter 2.3.1. To emphasize the need for a deeper analysis of external risks, especially natural disasters, a distinction is introduced that allows to separate risks in: risks that can be associated with specific procurement markets and those that are not market related (see chapter 2.3.2). A specialty in terms of risks that cannot be associated to specific procurement markets (like natural disasters) is that the participants within a supply chain network do not have any influence on their occurrence. Only possible impacts can be reduced through appropriate measures.

To reveal the current status on research about the influence of natural threats on supply chains and their performance, a second literature review is conducted, showing the research gap in that area. Within the analysis of supply chain risk assessment methods in chapter 4.4.1, evidence on the lack of information is given, as natural disasters are rarely included within assessments. If risks from outside the supply chain network are incorporated it is remarkable that those risks are usually associated to the supplier. Following the stated classification this may be valid for risks that can be connected to the procurement market and therewith partly to a supplier, but not for natural disasters. Moreover, only one source is identified that included external risks in the computation, all others - if at all - only mentioned that there are also external risks. None of the identified approaches investigated the impact of natural disasters on supply chain performance. On the other hand, there are several global and regional natural disaster risk indices, reports and assessment approaches in place, focusing on the threat itself (see chapter 4.4.2). But like supply chain risk assessment approaches lack the consideration of natural disasters, they do lack any relation to supply chains. At the moment no approach exists that evaluates the influence of natural disasters on supply chain performance. Therefore a new approach is developed and explained in chapter 6 in this work.

To evaluate the performance impact of natural disasters on supply chains it is necessary to focus on the region they take place, therefore the concept of vulnerability of places is used and introduced in chapter 5. To assess the susceptibility of a region and to enable comparability between different places, vulnerability factors and their explaining indicators had to be identified. The main categories the factors can be assigned to are social, economic, physical and environmental aspects. While social characteristics refer mainly to the social system within a region, economic criteria focus on the economic. Aspects of the built environment, like infrastructure, are subsumed within physical factors and ecological matters are classified as environmental vulnerability factors. Within each of the four categories the most referred to and suitable for the topic were chosen and used within the impact analysis in chapter 6.

To measure the performance impact, the value 'deviation in delivery times' is defined as indicating variable. As information about that key performance indicator is tracked in nearly every corporation, it is quantifiable and allows easy applicability for different corporations. The delivery deviation is the time between a requested date of delivery and the realized one. Due to the scare data basis the assumption is made that a corporation could at least not deliver as long it is closed after a disaster hit. There were 32 studies identified, dealing with business closure times after a natural threat. Based on the information given in the literature the severity distributions were calculated for the different countries stated. The severity distribution expresses thereby the extent of closure times. As the realization of an impact is also dependent on the probability of the triggering event, the frequency distributions were calculated with the help of historical data sets. To finally gain a total loss function the Loss Distribution Approach is chosen, as it enables the convolution of the frequency and the severity distribution to one distribution, which expresses the distribution of loss within a given time interval. The resulting value is also called delivery time at risk.

After the presentation of the necessary steps for the **S**upply **C**hain **perform**ance impact assessment of **N**atural **D**isasters (SCperformND) approach and the mathematical foundation in chapter 6, a case study emphasized the application of the developed approach. The first case study identifies the vulnerability indicators with the greatest influence on delivery time deviations, which are: birth rate (number of birth per 1000 population), forest area (% of total land area), roadways in km and population living in areas where elevation is below 5 meters (% of total population). The chapter closes with an in-sample model validation - evaluating the deviations between observed and calculated values. The key vulnerability indicators serve in the second case study as input variables to calculate the potential extent of delivery time deviations for the sample region which in this case is the USA. With the SCperformND approach it is therefore possible to compare different places based on the identified indicators and to calculate the delivery time deviations. Based on that information recommendations for supply chain design decisions are possible, like the selection of potential suppliers or location decisions for own production facilities. The higher the potential delivery time deviations after a natural disaster, the higher the potential risk to source / produce in this area. It must be taken into consideration that for example the benefits of low cost sourcing can easily be outweighed when a disaster strikes. The SCperformND approach hence suggests to choose a region with lower delivery time deviations if there are alternatives. If not, the potential impacts on supply chain performance should at least be known and appropriate measures should be implemented. With the SCperformND approach it is therefore possible to identify vulnerability characteristics with the greatest influence on delivery time deviations as well as the extent of delivery time deviations for a specific region and time horizon, enabling the evaluation of performance impacts of natural disaster on supply chain performance. The approach closes the research gap on supply chain risk assessment methods lacking the consideration of natural disaster, and the gap on natural disaster risk assessments lacking supply chain performance aspects. SCperformND is therefore a powerful tool, extending operational supply chain risk methods to a holistic assessment.

The work closes with a summary and critical appraisal as well as directions for future research.

8.2 Critical appraisal and directions for future research

As mentioned several times previously a practice partner would be an asset to gain real time data for the approach presented in this work. Although the principles of the **S**upply **C**hain **perform**ance impact assessment of **N**atural **D**isasters (SCperformND) approach were shown, additional data sets would enable the derivation of supply chain design recommendations for a specific corporation. Additionally the assumptions made, such as that a business could not deliver as long it is closed and that there are no measures in place to mitigate possible impacts, are obsolete, as the respective supply chain could be mapped in detail. Moreover, the simplification, that only direct connections between different locations are considered, has to be suspended for modeling a complex real world supply chain.

The small data base itself could also distort the presented results. To overcome this problem more research on business closure respectively delivery time deviations in the aftermath of a natural disaster is necessary or at least evaluations of real time data of a corporation. Hence the chosen indicator 'delivery time deviation' is tracked in nearly every corporation and is classified as KPI this could easily be done within a corporation. Therefore the available delivery data must be related to natural disaster events in the region of question. Above that it is due to the lack of data not possible to investigate the relevance of vulnerability indicators for different natural disaster types. This distinction might be useful as disaster types vary such as on speed of onset and duration. A broader data set could as well enable the test of combinations of more than four indicators as explaining variables for delivery time deviations, which is not possible here.

Furthermore, characteristics of a corporation can influence the extent of disaster impacts itself, which were not investigated, because the focus of this work is the vulnerability of regions and the evaluation of performance impacts based on characteristics of that area and not of a corporation. However this can bring further insights about which factors affect the impacts of natural threats on businesses.

Aside from that the transport of goods shall also be incorporated within an analysis, as the routes goods are transported by are at risk from natural disasters too. This aspect is excluded within the analysis of place specific vulnerability aspects in this work.

Another field of research is the investigation of smaller regions, like states. Based on the presented methodology it is possible to evaluate places of minor extent, when the relevant vulnerability indicators are first identified. Within future research several regions / places could be compared to others.

It might also be useful to extend SCperformND to an industry perspective, as some of the indicators identified might change in importance due to different requirements in distinct branches. Also the incorporation of business specific weights for the indicators could be investigated. Even the selection of another indicating variable for performance impacts can be evaluated, for some corporations a focus on the delivered quality might be an example instead of the presented delivery time deviations.

Future research should also focus on the extension of the approach presented with risk methods for operational risks. This is to gain an overall supply chain risk assessment. Only if all categories with potential for harms are considered, can risks be reduced effectively.

A Appendix

A.1 Reasons for increased supply chain vulnerability

Table A.1: Reasons for increased supply chain vulnerability

Reason	Source
Climate change	[182], p. 226
Changes of atmospheric means in the long term	[207], p.7
Increase in the frequency and intensity of extreme weather events / catastrophes / disaster / natural hazards	[57], p.189; [373], p.301; [58], p.1ff; [207], p.7; [192], p.108; [182], p.6, 237
Risk of epidemics	[399], p.2
Increased number of man-made hazards; external event: terrorism, war, political instability, terrorist attacks	[60], p.6; [399], p.2ff; [57], p.189; [58], p.1; [182], p.6
Industrial disputes; External event: strike	[58], p.1; [57], p.189
Infrastructure break-down	[182], p.6
Globalization, global sourcing, global supply chains, more global competition; globe spanning operations; more sales channels / markets; internationalization of markets	[301], p.25; [238], p.41ff; [58], p.1; [182], p.2; [300], p.12; [42], p.127; [313], p.242; [129], p.51; [373], p.302; [399], p.16f
Trend to outsource, outsourcing of supply networks across international borders; outsourced manufacturing, information technology, logistics; offshoring, off-shore manufacturing	[182],p.44; [129], p.51; [57], p.189; [300], p.12; [313], p.242; [299], p.451; [373], p.302
Sourcing in low-cost countries	[373], p.302
Centralization of production and distribution; centralization of manufacturing and warehousing; focused factories and centralised distribution	[399], p.1; [182], p.44; [313], p.246; [57], p.191; [122], p.1
Rationalization within the corporation	[182], p.2
Standardization efforts	[42], p.127
Changes in business strategy	[57], p.189

Reason	Source
Changes in business model	[57], p.189
Concentration on core competences	[182], p.44
Lean (production) initiatives, lean supply chains	[313], p.242; [58], p.1; [182], p.44; [42], p.127 [313], p.242; [57], p.189; [373], p.302; [55], p.54
Decreased stock; reduced inventory and slack	[313], p.242f; [399], p.1; [373], p.302; [22], p.4068
Increased responsiveness	[22], p.4068
Single sourcing, reduced number of suppliers; reduced size of supplier base; streamlining supply base; supply base reduction	[313], p.244; [399], p.1; [182], p.44; [300], p.12; [57], p.189; [42], p.127; [373], p.302
Shorter lead times	[313], p.244
More agile operations; higher level of agility	[373], p.302 [22], p.4068;
Just-in-time inventory systems	[300], p.12
Vendor-managed inventory	[300], p.12
Limited availability of scarce resources	[399], p.15
Fast technological developments	[182], p.2
Decrease of machine and Personnel capacity	[399], p.1
Cultural differences, cultural and language barriers	[399], p.2ff; [42], p.127
Interdependence of corporations; increased interfirm dependence; increased interconnectedness, high interconnectedness, close relationships; stronger interconnectedness of all stages of a value chain	[182], p.6,44; [373], p.302; [42], p.126; [313], p.244; [58], p.1ff

Reason	Source
Increased competition, fiercer competition	[399], p.1; [373], p.302
Collaborating more intensively with other supply chain actors	[373], p.302
More reliance on external sources; supplier dependence; supplier concentration	[373], p.304f
Increased customer dependence	[373], p.305
Increased product / service complexity and number of variants, great range of different products; greater variety; more product variety	[129], p.51; [313], p.244; [238], p.41; [299], p.451; [300], p.12
More frequent new product introductions	[300], p.12
More complex supply chains, increased complexity; long and complex global supply chains	[182], p.44; [58], p.1f; [238], p.41ff; [313], p.242; [373], p.302; [313], p.244; [42], p.126; [300], p.12; [375], p.97
Shorter product / technology life cycles	[55], p.54; [58], p3; [238], p.41; [57], p.189
E-business; online sourcing including e-markets and online auctions	[129], p.51; [300], p.12
Demand more volatile	[57], p.189
Focus on efficiency rather than effectiveness, focus on efficiency	[57], p.190; [313], p.246

A.2 Supply chain risk classification - sources

Table A.4: Supply chain risk classification - sources

Classification	Source
Supply chain-internal risks / Supply chain-external risks	[19], p.14
Physical / Financial / Informational / Relational / Innovational	[49], p. 384f
Supply Risk / Demand Risk / Process risk / Control Risk / Environmental Risk	[56], p.238
Internal risk sources / **External risk sources:** Customer risk sources, Supplier risk sources, Other risk sources	[135], p.502ff
Description	
External sources could also cause a glitch in the supply chain; Others: includes government, regulatory and **nature as source of responsibility for the glitch (e.g. weather related problems)**	
Environment-related risk sources / Organizational risks sources / network related risk sources	[156], p.114
Internal risks / External risks	[159], p.112
Set-up risks (strategic, ex-ante) / Partnering risks (strategic, ex-post) / Initiation risks (operative, ex-ante) / Transaction risks (operative, ex-post)	[224], p.26
Network risks / Process risks / Product risks / Infrastructure risks	[371], p.87
Strategic risk / Operations risk / Supply risk / Customer risk / Asset impairment risk / Competitive risk / Reputation risk / Financial risk / Fiscal risk / Regulatory risk / Legal risk	[129], p.53
Description	
Financial: Exposes a firms potential loss through changes in financial markets; can also occur when specific debts default Regulatory: Exposes the firm with changes in regulation affecting the firm's business, such as environmental regulation; categorized as 'indirect risks'	
Organizational risks / Network risks / **Environmental risks**	[187], p.100ff
Description	

Classification	Source
Environmental risks are beyond the influence of the members of the entire supply chain **(e.g. disasters / natural hazards [fire, hail, earthquake, storm, cold, avalanche, landslide, dike breach, rock slide, flood, pandemic];** import or export controls, war or terrorism, politics, national economy, currency)	
Environmental risk sources / Demand risk sources / Supply risk sources / Process risk sources / Control risk sources	[156], p.122f
Description	
Environmental: comprise any **external uncertainties arising from the supply chain such as disruptions caused by** political (e.g. fuel crisis), **natural** (e.g. foot and mouth break out, **fire, earthquake**) or social (e.g. terrorist attacks) **uncertainties**	
Supply risk / Process risk / Demand risk / **Corporate-level risks**	[245], p.22
Description	
Corporate-level: **risks to the entire supply chain** - supply side, within the organization and demand side – and hence to the enterprise itself (financial, supply chain visibility, political / social, IT systems, intellectual property, exchange rate)	
Supply risk / Demand risk / Process risk / Control risk **/ Environmental risk**	[57], p.194
Description	
Environmental: Where across the supply chain as a whole are we **vulnerable to external forces**? Whilst the type and timings of **extreme external events** may not be forecastable, their impact needs to be assessed	
Internal to the firm / External to the firm but internal to the supply chain network **/ External to the network**	[58], p.4ff
Description	
External: environmental: These events may directly impact upon the focal firm or on those upstream or downstream, or indeed on the **marketplace** itself. They may **affect a particular value stream** (i.e., product contamination) **or any node or link** through which the supply chain passes (i.e., **as a result of an** accident, direct action, **extreme weather or natural disasters**). They may be the result of sociopolitical, economic or technological events many miles or organizations removed from the focal firm's own supply chains, but may have **carry-over effects through linkages** to other industry networks. The type or timing of these events may be predictable (i.e., those arising from regulatory changes), but many will not be, though the impact of these type of events may still be assessed.	
Operational risks **/ Disruption risks**	[299], p. 453
Description	

Classification	Source
Disruption risks are referred to the major **disruptions caused by natural** and man-made **disasters such as earthquakes, floods, hurricanes,** terrorist attacks, etc., or economic crises such as currency evaluation or strikes	
Disruptions / Delays / Systems / Forecast / Intellectual property / Procurement / Receivables / Inventory / Capacity	[55], p.53ff
Description	
Environmental: Where across the supply chain as a whole are we **vulnerable to external forces**? Whilst the type and timings of **extreme external events** may not be forecastable, their impact needs to be assessed	
Internal to the firm / External to the firm but internal to the supply chain network / **External to the network**	[58], p.4ff
Description	
External: environmental: These events may directly impact upon the focal firm or on those upstream or downstream, or indeed on the **marketplace** itself. They may **affect a particular value stream** (i.e., product contamination) **or any node or link** through which the supply chain passes (i.e., **as a result of an** accident, direct action, **extreme weather or natural disasters**). They may be the result of sociopolitical, economic or technological events many miles or organizations removed from the focal firm's own supply chains, but may have **carry-over effects through linkages** to other industry networks. The type or timing of these events may be predictable (i.e., those arising from regulatory changes), but many will not be, though the impact of these type of events may still be assessed.	
Operational risks / **Disruption risks**	[299], p. 453
Description	
Disruption risks are referred to the major **disruptions caused by natural** and man-made **disasters such as earthquakes, floods, hurricanes,** terrorist attacks, etc., or economic crises such as currency evaluation or strikes	
Disruptions / Delays / Systems / Forecast / Intellectual property / Procurement / Receivables / Inventory / Capacity	[55], p.53ff
Description	
Disruptions to material flows in the supply chain **are unpredictable and rare but often quite damaging** (e.g. **natural disaster**, labor dispute, supplier bankruptcy, war and terrorism, dependency on a single source of supply as well as the capacity and responsiveness of alternative suppliers	
Internal risks / **External risks**	[313], p.244
Description	

Classification	Source
External: deal **with environmental causes that can barely be influenced** and lead directly or indirectly to disturbances within the supply chain (sociopolitical, economical, technological or **geographical reasons [earthquakes or hurricanes** as well as terrorist attacks or political instabilities])	
Demand-side risk / Supply-side risk **/ Catastrophic risk**	[373], p.304
Description	
Catastrophic: This class subsumes supply chain **disruptions** that, when they materialize, have a **severe impact in terms of magnitude in the area of their occurrence** (This refers to **natural hazards (force majeure)**, socio-political instability, civil unrest, economic disruptions, and terrorist attacks)	
Supply risks / Process risks / Demand risks / Intellectual property risks / Behavioral risks / Political / social risks	[300], p.13f
Description	
Political / Social: a supply chain is subjected to social / political risk when multiple countries are involved	
Environmental risk sources / Network-related risk sources / Organisational risk sources	[157], p.201f
Description	
Environmental: comprises any **uncertainties arising** from the **supply-chain-environment interaction** (accidents [e.g. fire], socio-political actions [e.g. fuel protests or terrorist attacks] or **acts of God [e.g. extreme weather or earthquakes]**)	
Plan risk / Source risk / Make risk / Deliver risk / Return risk Subclassification: ’People , Organization’ / ’Process , Material’ / ’Infrastructure’ **/ ’Environment’**	[399], p.26ff
Description	
Environment: risk **cause outside the influence of the supply chain (e.g. forces of nature [fire, hurricanes]**, unplanned waiting times at customs)	
Internal supply chain risks **/ External supply chain risks** Or within portfolio theory: **Systematic supply chain risk /** Unsystematic supply chain risks	[298], p.60ff
Description	
External: occur outside the supply chain (disturbance of material-, information- and / or financial flows) Systematic: outside the supply chain, **not influenceable**	
Supply chain internal risks **/ Supply chain external risks**	[294], p.275f

Classification	Source
Description	
External: as a **result of the interaction of the supply chain with its environment**; affect the supply chain as a whole (e.g. labor dispute, terrorist attacks, **natural disaster**, risk caused by social-cultural or legal-political changes)	
According to global circumstances (macro-environment) / According to task-specific circumstances (competitive environment)	[220], p.13ff
Description	
Global environment: economic-, social-cultural-, political-legal-, technological environment Task-specific: customers (disruptions to production performances can also be caused by acts of God, like **natural disasters (earthquakes, floods, etc.)** or corporate disasters (accidents, fire, explosion etc.)), suppliers, new competitors, substitution product or services, dynamic of competition	
Supply-chain-external risks, related to specific procurement markets (environmental risks) / Supply-chain-internal risks (supply risk) **/ Supply-chain-external risks, not related to specific procurement markets (external environmental risks)**	[168], p.68ff
Description	
Supply-chain-external, **related to specific procurement markets:** result of **characteristics and circumstances of the global procurement market** (political risks, legal risks, economic risks, socio-cultural risks, technological risks) Supply-chain-external, **not related to specific markets: natural hazards**, risks of low cost country sourcing, which cannot be assigned to a specific country	
Enterprise risk: core business risk **/ non-core business risk** Core business risk: value chain risk / operational risk Non-core business risk: event risk / recurring risk (credit risk / tax risk / market risk) **Event risk:** legal / regulatory / political / hazard / economic **/ natural /** reputation	[239], p.221ff
Description	
Market risk: the uncertainty caused by fluctuations in the market prices, changes in foreign exchange rates, changes in interest rates, price changes for commodities Business risk: uncertainty associated with key business drivers (e.g. the overall state of the economy, fluctuations in customer demand, supply disruptions, competitive actions by rivals, technological change, legal liabilities, regulatory changes) Event risk: no description	

Classification	Source
Environmental factors / Industry factors / Organizational factors / Problem-specific factors / Decision-maker related factors **Environment risk:** political uncertainty / Policy uncertainty / Macroeconomic uncertainty / social uncertainty / **natural uncertainty**	[227], p.101ff
Description	
Environmental risk: variables that **affect the overall business context across industries,** while the magnitude of this impact across different industry sectors may be different Political uncertainty: major changes in political regimes; weak government; potential or actual changes in the political system as a result of war, revolutions, coup d'état, or other political disturbances Policy uncertainty: refers to changes in government policy that impact the business community (e.g. fiscal and monetary reforms, price controls, minimum-wage agreements, or nationalization / privatization) Macroeconomic uncertainty: incorporating fluctuations in the level of economic activity and prices (e.g. general price change in the cost of goods (inflation) or movements in the relative prices of inputs such as raw material or labor, exchange rates, and interest rates) Social uncertainty: follows from the beliefs, values, and attitudes of the population that are not reflected in the current government policy or business practice (e.g. threat to the supply chain from activities of terrorism) **Natural uncertainty:** include various phenomena such as **earthquake, floods, and fires,** which could **impair business functions** and **decrease the productive capacity** of firms operating in the affected region	
Uncertainty between node enterprises / uncertainty in node enterprises / uncertainty of market demand / **uncertainty of external environment** **Environmental risk: natural environment risks** / social environment risks / economic risks	[390], p.2f
Description	
Uncertainty in the **external environment:** will **affect node enterprises and** thus affects the **stability of the entire supply chain** (e.g. **natural** and man-made **disasters**, political instability, war, accidents) **Natural environment risk: natural disasters** Social environment risk: terrorist incidents, crises Economic risks: depression, economic slide	
Customer risks / Supplier risks / Bureaucratic risks / Infrastructural risks / **Catastrophe risks**	[376], p.102
Description	

Classification	Source
Catastrophe risks: natural disasters / Terrorism, war, unrest,	
Risks - with source inside the corporation / Risks - outside the corporation, but internal to the supply chain **/ Risks - outside the supply chain (within the environment)**	[141], p.116f
Description	
Environmental risks: referring to risks that arise outside the supply chain, and have direct or indirect impacts on an element of a supply chain or a flow within the supply chain	
External risks / internal risks **External risks:** political risks / Economy risks / Culture risks / Technical risks / **Natural risks** / Demand risks Political risks: law (imperfect laws, trade barriers, strict environment policies) / social order (regime change, war, terrorism) / world economy (depression of world economy) Culture risks: culture background (culture differences between countries) Technical risks: R&D of products (accelerated R&D innovation) **Natural risks: natural disaster (earthquakes, hurricanes, tsunamis)** / climate (random variation of wind, wave, tide) Demand risks: Substitutive products (increased substitutes) / rivals (increased competitors)	[73], p.1152
Description	
External risks: refers to those risks exposed to external environment	
Supply risks / Operational risks / Demand risks **/ Other risks**	[148], p.197ff
Description	
Other: risks are **beyond the direct control of any entity in the supply chain**, aggravate the impact of other risk events, and include currency fluctuations, wage rate shifts, and events that comprise the security of the supply chain; culture (inadequate knowledge about people, culture, and language); oil price increase (change in oil price) Security risks: is the distribution of outcomes related to adverse events that threaten human resources, operations integrity, and information systems; and may lead to outcomes such as freight breaches, stolen data or proprietary knowledge, vandalism, crime, and sabotage	

A.3 Factors in social vulnerability

Table A.11: Factors social vulnerability

Factor	Sub-factor	Indicator(s)	Hazard type	Source
cultural aspects / traditions /religion				
(positive) traditional knowledge systems and values, traditions, indigenous and social beliefs, customs			G	[166], p.193 [392], p.381 [332], p.42 [67], p.245
disruption of cultural practice (tourism, religious practices), cultural aspects			G	[149], p.20 [139], p.7
cultural heritage values		identification of cultural heritage sites (international, national, local interest), Variable: traditional forest practices, traditional fire use, cultural practices on forest	FF	[190], p.102
religion / social needs			G	[139], p.7
preparedness / risk awareness				
risk perception	perception of risk and approach towards emergencies (cultural beliefs)		G F	[166], p.193 [190], p.117 [237], p.85ff
flood risk awareness, flood beliefs			F	[190], p.117
knowledge of warning systems			F	[190], p.117
attitudes and responsibilities, attitudes on self precaution		priority of population to protect against a hazard	G F	[25], p.276 [190], p.117

Factor	Sub-factor	Indicator(s)	Hazard type	Source
prevention & preparedness		disaster prevention & preparedness (US$/year/capita)	D	[47], p.113
access to information and press freedom, (lack of) access to resources (including information, knowledge, technology, safe sanitation)		number of mobile phones, TVs, radios/per capita	G F C	[237], p.88 [166], p.193 [67], p.245 [121], p.6 [45], p.27 [333], p.4
ways of coping, coping strategies (incl. farming methods and land tenure systems)			G	[237], p.85ff [332], p.42
individual's characteristics				
age, very young and very old, age groups	elderly (more dependent, less resistant, mobility constraints)	percent of population under 5 / 18 / 20 and above 64 / 65 / 75 (living alone), median / average / functional age, population ages 15-64 / 20-64 (% of total population), elderly households / city district [%], elderly population divided by gender, age dependency ratio	G F HW L FF C	[392], p.382ff [71], p.21 [139], p.7 [332], p.42 [29], p.934 [67], p.243ff [138], p.27 [205], p.82 [126], p.115 [41], p.143 [68], p.103 [89], p.5 [132], p.2ff [389], p.6

Factor	Sub-factor	Indicator(s)	Hazard type	Source
				[47], p.113 [190], p.34, 63f, 101, 118 [243], p.63 [237], p.88ff [59], p.22 [33], p.1618 [217], p.1 [333], p.102
gender	female, male, households security, nutrition, health, gender inequality	percent females, percent female headed households (no spouse present), gender per percentage of total population, the distribution of males and females by age, GDI (Gender-related development index)	G	[392], p.381f [71], p.21 [45], p.23 [139], p.7 [332], p.42 [29], p.934 [67], p.245ff [389], p.7ff [93], p.158f [96], p.119f [133], p.5ff [107], p.35f [189], p.238f [138], p.27 [65], p.533 [205], p.82

Factor	Sub-factor	Indicator(s)	Hazard type	Source
				[126], p.116ff [94], p.131ff [41], p.137ff [89], p.5ff [132], p.2ff [68], p.103ff [383], p.330 [243], p.63 [237], p.89ff
population				
population density, exposed population	coastal settlements	number of housing units per square mile, number of housing permits per new residential construction per square mile, total human population density (persons/km^2), number of households, density of people living in coastal settlements within a city center within 20 km of the coast (persons/km^2)	G F D L FF C	[398], p.254 [29], p.934 [67], p.250 [333], p.3, 102 [121], p.6 [163], p.32 [243], p.63 [25], p.276 [161], p.17 [217], p.1 [59], p.22 [378], p.1932 [190], p.100f

Factor	Sub-factor	Indicator(s)	Hazard type	Source
population		total resident population, number of total population in country, small population	G	[25], p.276 [318], p.40 [243], p.68
special needs population, disabled, frail and physically limited individuals, physically or mentally challenged		disabled population (number of disable residents within the county or region), homeless, tourists, transients, nursing home residents, per capita residents in nursing homes, people disability	G FF	[392], p.383ff [71], p.21 [332], p.42 [67], p.245ff [126], p.116 [132], p.10 [149], p.101
rural population		rural population (% of total population)	D	[47],p.113
population change 1990/2000		percent population change	CH	[29], p.934 [67], p.250
net international migration, migrant populations		net international migration, foreigner / city district [%] (proxy: problems in understanding warning messages), migrants in country for less than 2 years	G F HW FF C	[29], p.934 [67], p.250 [333], p.4 [190], p.63f, 101
population located on coastal plains			D C	[333], p.3
homeless			G	[67], p.245
refugees		refugee population by country or territory of asylum (% of total population)	HW	[47], p.113
education				

Factor	Sub-factor	Indicator(s)	Hazard type	Source
population growth, growth rates	urban growth	rapid growth, birth rate (number of birth per 1000 population), annual human population growth rate (percent) (average over last 5 years)	G F	[392], p.383 [71], p.21 [29], p.934 [67], p.248ff [126], p.117 [127], p.154 [25], p.276 [161], p.17 [217], p.1 [121], p.6 [32], p.1618 [333], p.102
education	educational commitment, entitlement to information	education expenditure as % of GNP / government expenditure, literacy rate (% of population over 15 / 15-24 / female to male), percent of population 25 years or older with no high school diploma, % less than high school, % of adult population that can read and write, school enrollment, Secondary (% gross), labor force with primary, secondary or tertiary education	G F C	[392], p.381 [71], p.21 [139], p.7 [332], p.42 [126], p.116f [67], p.248ff [1], p.81 [237], p.85ff [166], p.193 [47], p.113 [333], p.102 [218], p.54 [25], p.276 [217], p.2

Factor	Sub-factor	Indicator(s)	Hazard type	Source
lack of proficiency in English, non-English speaking immigrant		percent of population not proficient in English	G	[392], p.385
family / household / insurance				
family structure, size of household, people per household		% single parent households, large families, average number of people per household, number of persons per household, one person household	G FF	[392], p.383 [71], p.21 [67], p.248ff [132], p.10 [126], p.116 [243], p.62 [139], p.7 [149], p.20,100f
family related insurance, individual and family related insurance			G	[237], p.85ff
absence or lack of motivation / opportunity		dwellings used as first residence, absentee homeowners / landowners, renter houses	FF	[190], p.101
employment / occupation				
occupation	agricultural occupation	% agricultural workers, % low skilled service jobs	G D	[71],p.21 [67], p.248 [126], p.116f [225], p.316ff [163], p.32

Factor	Sub-factor	Indicator(s)	Hazard type	Source
employment, employment loss		% unemployed / unemployment rate (city district [%]), percent of population / females participating in labor force, percent employed in primary extractive industries (farming, fishing, mining, and forestry) / in transportation / communications / other public utilities / in service occupations,	G F HW C	[71], p.21 [139], p.7 [29], p.934 [67], p.243ff [183], p.239 [333], p.102 [149], p.20 [190], p.34,63
health				
health and nutrition, public health, human health sensitivity, disability	access to nutrition	Food price index (annual change averaged over 1981-90 and 1991-99)	G	[36], p.155 [1], p.81
	incidence of tuberculosis (TB)	incidents of tuberculosis (TB) per 10000 people for any given year	G	[244], p.104
	biophysical sensitivity of human health	current temperature	G	[112], p.22
	socio-economic exposure of human health	population in disaster hot spots	G	[112], p.22
	fertility	completed fertility	G	[31], p.67,98
	health status	GHG emissions (cumulative CO^2 emissions per cap. since 1990 from fossil / all sources	G	[166], p.193 [67], p.243 [112], p.22
	chronic health conditions	respiratory diseases, people with mental disorders	FF	[190], p.101
	physical strength		G	[237], p.85

Factor	Sub-factor	Indicator(s)	Hazard type	Source
	physical, mental and psychological well-being		G	[332], p.42
vaccination		number of people vaccinated, legal regulations for vaccinations	F D C	[237], p.91ff
occupation	agricultural occupation	% agricultural workers, % low skilled service jobs	G D	[71],p.21 [67], p.248 [126], p.116f [225], p.316ff [163], p.32
social vulnerability (lack of adaptive capacity) of human health		Human Development Index, physical capital stock per capita, government effectiveness, vulnerability index for mortality from natural disasters	G	[112], p.22
medical services, access to medical services		higher density of medical establishments and services, per capita number of community hospitals, number of physicians per 1000,000 population	G	[392], p.383 [71], p.21 [67], p.248ff [137], p.157
security				
social insecurity			G	[332], p.42
existence of peace and security			G	[332], p.42
government / governance				
legal situation, laws, ownership structure, (access to basic) human rights			G	[166], p.193 [332], p.42

Factor	Sub-factor	Indicator(s)	Hazard type	Source
citizen participation, social organizations, institutions (civil society), institutional organizations			G	[166], p.193 [332], p.42
power structures and conflicts, limited access to political power and representation, relationship to decision makers, social and political structure, social power relations, persons in structures			G L	[166], p.193 [67], p.245 [126], p.117 [332], p.42 [59], p.22
politics and corruption			G	[166], p.193
collective organizational systems			G	[332], p.42
government		government effectiveness	D	[47], p.113
governance, systems of good governance			G	[332], p.42
integration in communities		temporary residents and holidaymakers, no or low level of ethnic minorities integration, migrants in country for less than 2 years	FF	[190], p.101
social cohesion and regulation			G	[332], p.42

Factor	Sub-factor	Indicator(s)	Hazard type	Source
conflicts				
community fragmentation	armed conflicts with involvement of the community	existence of conflicts inside community (existence of internal conflicts / with organized groups / with government agencies), intra- and inter communal conflicts and their intensity, number of wars or civil uprisings over the last 50yr within the territory (years)	G FF	[190], p.101 [237], p.89 [121], p.6
tourism / recreation				
tourists, seasonal tourists		annual number of international tourists * average days stay/365/ sq km (last 5 years)	G	[161], p.17 [67], p.245
recreational areas		boat launch sites (#), fishing hot spots (#), swimming beaches (#), sports facilities, coastal public property (state owned land)	CH SL CE OCH EW	[213], p.1393
(socio) economic status				
poverty and dependencies, rural poverty		dependency ratio (share of under 15- and over 65-year-olds in relation to the working population), extreme poverty population living with USD 1.25 per day or less (purchasing power parity)	G F D	[318], p.40 [333], p.5

Factor	Sub-factor	Indicator(s)	Hazard type	Source
income, income opportunities, (personal) savings		GDP per capita	G L	[237], p.85ff [45], p.27 [59], p.22
social class, class or caste structure	employment (type and stability), income, savings, education levels, income distribution, asset holding, livelihood qualifications & opportunity	less privileged	G	[392], p.381f [45], p.23 [332], p.42 [94], p.132f [41], p.142 [394], p.537 [66], p.118 [108], p.91 [24], p.22 [95], p.117, 132 [389], p.6,11,35
social inequalities		Deprivation Index, Multidimensional Poverty Index	FF	[190], p.101
social equity			G	[392], p.381 [332], p.42
social capital, including social networks and connections, family and social networks, neighborhood network			G F	[67], p.245 [126], p.117 [237], p.88ff [190], p.117

Factor	Sub-factor	Indicator(s)	Hazard type	Source
social dependence		% / per capita social security recipients, recipient of social benefit/city district [%], (Proxy: low income)	G F	[71], p.21 [67], p.249f [190], p.64
way of life			G	[138], p.27
Human Development Index			G	[218], p.54
natural disaster				
social-ecological pressure	Exposure to hazards	Climate Hazard Index (CHI)	EW	[98], p.185
	sensitivity to hazards	Population Density Index (PDI), Protected Area Density Index (PAI)	G	[98], p.185
infrastructure / access to resources				
water source		improved water source (% of rural population with access)	D	[47], p.113
social vulnerability (lack of adaptive capacity) of food		Human Development Index, physical capital stock per capita, government effectiveness, prevalence of undernourishment	G	[112], p.22
social vulnerability (lack of adaptive capacity) of water		Human Development Index, physical capital stock per capita, government effectiveness, households with improved water supply	G	[112], p.22
built environment				
exposed buildings		number of buildings	FF	[149], p.100f
ratio of secondary houses			G	[149], p.20

Factor	Sub-factor	Indicator(s)	Hazard type	Source
ethnicity				
race and / or ethnicity, participation and inclusion of minorities, (ethnic) minorities, cultural community	status of community	% African Americans / Hispanic / Asian / Native American, status of ethnic groups	G F C	[392], p.381f [71], p.21 [45], p.23 [67], p.234ff [389], p.15 [205], p.82 [94], p.134 [41], p.142 [333], p.4 [243], p.64 [166], p.193 [332], p.42 [237], p.85ff
economy				
subsistence economy in primary sector		productivity per capita (primary sector)	G	[237], p.88ff

A.4 Factors in economic vulnerability

Table A.25: Factors economic vulnerability

Factor	Sub-factor	Indicator(s)	Hazard type	Source
socio (economic) status				
socioeconomic status (income, political power, prestige), poverty		% poverty per capita income, annual household income, percent of households earning more than $75,000	G	[166], p.193 [67], p.246ff [183], p.46 [389], p.15 [216], p.28, 168,176 [225], p.297 [205], p.82 [126], p.115
income and economic structure, household income		(annual) per capita income (in dollars)	G	[166], p.193 [45], p.26f [139], p.7 [111], p.158 [29], p.934 [67], p.243 [383], p.330
economic capacity and income distribution, economy, GDP (per capita), national wealth		GDP per capita (purchasing power parity / current US$), Gini index, total locally generated GDP in constant currency	G F HW C	[318], p. 40 [47], p.113 [333], p.3,102 [149], p.20 [218], p.54 [25], p.276

Factor	Sub-factor	Indicator(s)	Hazard type	Source
				[166], p.193 [45], p.26f [1], p.81 [217], p.1
economic reserves, reserves		levels of individual, community and national economic reserves	G	[166], p.193 [45], p.26f [332], p.42
inequality		GINI coefficient	G	[166], p.193 [45], p.26f [1], p.81 [243], p.63
(absolute) poverty, food situation, poverty headcount		percent of population living in poverty, poverty level, GDP per capita, per capita social security recipients, % of population below poverty level, Human Poverty Index (HPI), poverty headcount ratio at 1.25 a day (PPP) (% of total population)	G D	[166],p.193 [45], p.26f [332] [29], p.934 [67], p.250 [392], p.385 [243], p.61 [25], p.276 [217], p.1 [333], p.102 [47], p.113
size of domestic market / resource base				

Factor	Sub-factor	Indicator(s)	Hazard type	Source
economic openness	size of country's domestic market, availability of resources in a country and ability efficiently to produce the range of goods / services required	ratio of international trade to GDP	G	[166], p.193 [45], p.26f
local resource base		total available local budget in US$	G	[25], p.276
narrow economic base			G	[243], p.68
small size	limited natural resource endowments and high import content (in relation to GDP), limitations on import-substitution possibilities, small domestic market and dependence on export markets, dependence on a narrow range of products, limited ability to influence domestic prices / to exploit economies of scale, limitations on domestic competition, problem of public administration	population, land area and / or gross national product	G	[166], p.193 [45], p.26f [333], p.3
finance / insurance				
access to credit, loans and insurance		degree of access to credit, loans and insurance	G	[332], p.42
lack of effective insurance systems, insurance services		remittances from abroad, urban population growth, transportation and communication network, number of missing values of important indicators	G	[243], p.63 [237], p.89

Factor	Sub-factor	Indicator(s)	Hazard type	Source
financial reserves and insurance			G	[166], p.193 [45], p.26f
dependence on foreign sources of finance			G	[166],p.193 [45], p.26f
level of debts, foreign debt burden		general local government debt to revenue ratio, total debt service (% of the exports of goods and services)	G F	[166], p.193 [45], p.26f [332], p.42 [29], p.934 [67], p.250 [243], p.69
debt service ratio			G	[218],p.54
economic autonomy		debt repayments (% GINI, averaged over decadal periods)	G	[166], p.193 [45], p.26f [1], p.81
technology / research				
technology, technical innovations, research and development	commitment to and resources for research, capacity to undertake research and understand issues	R&D investment (% GNP), scientists and engineers in R&D per million population	G	[166], p.193 [45], p.26f [1], p.82 [243], p.68
government / governance				

Factor	**Sub-factor**	**Indicator(s)**	**Hazard type**	**Source**
state	institutional support, training, regional bias		G	[166], p.193 [45], p.26f
level of debts, foreign debt burden		general local government debt to revenue ratio, total debt service (% of the exports of goods and services)	G F	[166], p.193 [45], p.26f [332], p.42 [29], p.934 [67], p.250 [243], p.69
economic autonomy		debt repayments (% GINI, averaged over decadal periods)	G	[166], p.193 [45], p.26f [1], p.81
governance	conflict, priorities other than adaption	internal refugees (1000s) scale by population	G	[166], p.193 [45], p.26f [1], p.82
	effectiveness of policies, politic	control of corruption, Transparency's CPI (Index of corruption)	G	[166], p.193 [45], p.26f [1], p.82 [217], p.2
	ability to deliver services	government effectiveness	G	[166], p.193 [45], p.26f [1], p.82
	willingness to invest in adaption	political stability, rule of law	G	[166], p.193 [45], p.26f [1], p.82

Factor	Sub-factor	Indicator(s)	Hazard type	Source
	barriers to adaption	regulatory quality	G	[166], p.193 [45], p.26f [1], p.82
	participatory decision making, information availability and citizens participation mechanisms in public decisions, community participation	voice and accountability, % voter turn out last communal elections	G	[166], p.193 [45], p.26f [1], p.82 [149], p.20 [25], p.276
	Influence on political process	civil barriers, political rights, civil liberties	G	[166], p.193 [45], p.26f [1], p.82
administrative community	civil protection means		G	[237],p.85
lack of strong central government			G	[243],p.64
political authority			G	[138]p.27
relation between the local / state authorities			G	[149], p.20
institutional dimensions	legislation constraints	planning legislation and practices, top-down decisions and actions	FF	[190], p.102
	state attitude	conflicts between agencies, fire agencies prescriptive, bureaucracy, disempowerment	FF	[190], p.102
	fire service evaluation of property defensibility	houses defensibility, forest defensibility	FF	[190], p.102

Factor	Sub-factor	Indicator(s)	Hazard type	Source
political upheavals			G	[243], p.65
regulators environment		type of government / number of signed international agreements	G	[237], p.85ff
armed conflicts with involvement of national government		number and intensity of conflicts	G	[237], p.88
administrative community	degree of autonomy / participation in decision making procedures and access to resources	density of rural population, level of urbanisation, level of corruption	G	[237], p.88
national and international political economy	manner in which surplus is generated and allocated, social power and control, civil security (war), demographic shifts (growth, migration, urbanization), debt crises, environmental degradation		G	[166], p.193 [45], p.26f
preparedness				
lack of warning systems, early warning capacity / system (preparedness), presence and quality of civil protection, incl. early warning / emergency plans / disaster management capacities/ forecast		number of radios (per 1000 inh.), density of rural population, level of urbanisation, level of corruption	G F C	[166], p.193 [45], p.26f [217], p.2 [333], p.102 [383], p.330 [237], p.88
high degree of (disaster) preparedness, prevention		experience with damaging floods, catastrophe information material, early warning system, emergency plans, firefighter stations, hospital within 30 km^2,		

Factor	Sub-factor	Indicator(s)	Hazard type	Source
		density of rural population, level of urbanisation, level of corruption, legal flood regulations, flood protection measures	G	[166], p.193 [45], p.26f [237], p.88ff
access to information			G	[111], p.158
national disaster management / planning			G	[237], p.85ff
(inadequacy of) mitigation measures, disaster prevention			G	[166], p.193 [45], p.26f [237], p.85
incentive- and sanction systems for risk reduction			G	[166], p.193 [45], p.26f
emergency management system and capacities			G	[237], p.88ff
development status				
development status	population structure	number of IDPs and refugees	G	[237], p.88ff
development		Human Development Index (HDI)	G F D C	[217], p.2 [333], p.102
economic dependency		fertility rate, sex ratio, age average, trading activities - rate of GDP, external aid ratio of GNI, contribution of primary sector to GDP	G	[237], p.88

Factor	Sub-factor	Indicator(s)	Hazard type	Source
commercial and industrial development		number of manufacturing / commercial establishments per square mile, earnings (in $ 1000) in all industries per square mile	G	[166], p.193 [45], p.26f [29], p.934 [67], p.246ff [383], p.330
tourism				
touristic turn-over			G	[149], p.20
dependence on foreign tourists or combinations of overseas investment and aid		tourism can degraded the land by destruction of wetlands and mangrove forests	G	[243], p.68
Infrastructure / access to resources				
transport network		highways, primary / secondary roads, railway	G	[190], p.35
infrastructure & health care system, infrastructure / services, accessibility, access to resources and services (water, energy, health, transport)		traffic infrastructure/road network	G	[237], p.85ff [166], p.193 [45], p.26f
access to sufficient food			G	[243], p.61
access to safe drinking water			G	[243], p.61
public funds availability (support beach protection works, cost of reposition of infrastructures)			G	[149], p.20
energy consumption				

Factor	Sub-factor	Indicator(s)	Hazard type	Source
energy consumption		energy consumption per capita (Million Btu per person)	G	[47], p.113
Networks				
social networks, loose social and economic networks			G	[111], p.158 [333], p.4
Employment				
employment by sectors		employment in agriculture / mining / production and construction / service sector	G	[190], p.35
employment		unemployment, total (% of total labor force)	G	[217], p.1
built environment				
type of dwelling unit			G	[67], p.243
economy				
economic system			G	[237], p.88
Decentralisation		portion of self-generated revenues of the total budget	G	[25], p.276
type of economic(al) / commercial activities		%age of arable land and permanent crops, arable land (in thousand hectars)	G F C	[217], p.1 [333], p.102
		%age of urban population	G F C	[217], p.1 [333], p.102

Factor	Sub-factor	Indicator(s)	Hazard type	Source
		%age of country dedicated to cropland	G	[217], p.1
		%age of agriculture's dependency for GDP	G D	[217], p.1 [333], p.102
		%age of labor force in agricultural sector	G D	[217], p.1 [333], p.102
	dune mining		SL CE OCH EW	[213], p.1393
	forest plantation		SL CE OCH EW	[213], p.1393
	sugar cane		SL CE OCH EW	[213], p.1393
	commercial & industrial buildings		SL CE OCH EW	[213], p.1393
	commercial farms		SL CE OCH EW	[213], p.1393

Factor	Sub-factor	Indicator(s)	Hazard type	Source
economic vitality			G	[67], p.243
agriculture, dependence on primary commodities	dependence on agriculture	agricultural employees (% of total / male / female population), rural population (% of total), value of all property and farm products sold per square mile, livestock / km^2, agriculture (% of GDP)	G	[166], p.193 [45], p.26f [29], p.934 [67], p.250 [383], p.330 [1], p.82 [243], p.66ff [47], p.113
	agricultural self-sufficiency	agricultural production index (1985, 1995)	G	[166], p.193 [45], p.26f [1], p.82
economic		Total dept service (% of the exports of goods and services)	G	[217], p.1
subsistence sites		subsistence fishing / harvesting / farming sites / areas (#)	SL CE OCH EW	[213], p.1393
small businesses		% of businesses with fewer than 20 employees	G	[25], p.276
lack of capital and assets			G	[243], p.63
professional dependence to the territory (fishing activities, tourism), family income			G	[149], p.20
ecosystem services		food production, raw materials	G	[190], p.35

Factor	Sub-factor	Indicator(s)	Hazard type	Source
crop production			D	[163], p.32
seed, farming structures, technology			G	[166], p.193 [45], p.26
diversification, ((limited) economic) diversity		economic sector mix for employment, lack of diversity	G	[25], p.276 [28], p.26 [332], p.42 [166], p.193 [45], p.26f
inflation, food prices		inflation, food prices (annual %)	G F C	[333], p.102 [217], p.1
health				
public expenditure on health as per cent of GDP			G	[218], p.54
Disruptions				
disruption of productive activities, loss of production		forest / agriculture productive areas (loss of production / jobs), industrial and service activities (loss of production / jobs)	FF	[149], p.20
disruption of livelihoods		loss of livelihoods (permanent, long duration, short duration), families income dependence from forest	FF	[190], p.101
accessibility		number of interruption of road access in the last 30 years	G	[25],p.276

Factor	Sub-factor	Indicator(s)	Hazard type	Source
dependence				
export concentration		UNCTAD index of merchandise trade	G	[166], p.193 [45], p.26f
dependence on strategic imports	depends on: country size, resource endowments / possibilities for import substitution	ratio of the imports of energy / food / industrial supplies to GDP	G	[166], p.193 [45], p.26f
insularity and remoteness	high per-unit transport (require small / fragmented cargoes), uncertainties of supply (time delays, unreliable transport service), large stocks		G	[166], p.193 [45], p.26f
land use / land cover				
landscaping planning law and procedures			G	[149], p.20
land use / land cover		crop, pasture, woodland	G	[190], p.35 [138], p.27 [195], p.182ff

A.5 Factors in physical vulnerability

Table A.39: Factors physical vulnerability

Factor	Sub-factor	Indicator(s)	Hazard type	Source
quality / construction / building characteristics				
technical construction method, quality of (human) settlements and buildings (housing type and construction, infrastructure, lifelines), siting of buildings			G	[166], p.193 [67], p.245 [138], p.27 [237], p.85
site, design and materials used for housing			G	[332], p.42
quality and age of building		building construction date combined with law enforcement considering earthquake safety	F D C	[237], p.90
main building material		buildings general stability varies depending on the building material used	F D C	[237], p.90ff
size / height of building		number of floors, number of families / residential building	F D C	[237], p.90
building stock and age			G	[67], p.245
built environment			G	[67], p.245
buildings		1-2 / > 3 households (per building), tourism relevant buildings, offices, commercial buildings, industry	G	[190], p.31

Factor	Sub-factor	Indicator(s)	Hazard type	Source
buildings susceptibility		Ignitibility of buildings materials, housing security	FF	[190], p.101
property				
housing tenure (ownership), tenure type		median dollar value of owner-occupied housing, median rent (in dollar) for renter-occupied housing units, percent renter-occupied housing units	G	[71], p.21 [29], p.934 [67], p.250 [89], p.5
residential property	residential erven	percent housing units that are mobile homes	G SL CE OCH EW	[67], p.247ff [126], p.114f [69], p.726 [213], p.1393
renters		percent renter-occupied housing units	G	[67], p.247ff [126], p.114ff [132], p.7ff
infrastructure / access to resources				
(lack of) basic infrastructure, insufficient basic infrastructure, public /strategic infrastructure and services	isolation of rural communities, commitment to rural communities, quality of basic infrastructure, water supply, sanitation	roads (km, scaled by land area with 99% of population), rural population without access to safe water (%), population with access to sanitation (%), piers (#), roads, railway lines, lighthouses, share of the population without access to improved sanitation / access to an improved water source	G SL CE OCH EW	[166], p.193 [398], p.245 [36], p.155 [332], p.42 [138], p27 [213], p.1393 [1], p.81f [318], p.40

Factor	Sub-factor	Indicator(s)	Hazard type	Source
Site, design and materials used for critical infrastructure			G	[332], p.42
infrastructural factors	agricultural irrigated land	agricultural irrigated land (% of total agricultural land)	D	[47], p.133
	renewable water	% of retained renewable water	D	[47], p.133
	road density	road density (km of road per 100 sq. km of land area)	D	[47], p.133
critical infrastructure		sewage plant, waste deposit, gas stations	G	[190], p.31
transport infrastructure		highways, primary / secondary roads, railway	G	[190], p.31
resistance and state of maintenance for structures			L	[59], p.22
critical buildings		transport and communication, infrastructure, hospital, kindergarten, nursing homes, primary schools / kindergarten	G	[190], p.31f
structures		liveliness (% of homes with piped drinking water)	G	[25], p.267
water	municipal / industrial / agricultural water		D	[163], p.32
settlement / infrastructure sensitivity		population no access clean water / sanitation	G	[31], p.66, 97 [243], p.67
building of new roads			L	[243], p.68f

Factor	Sub-factor	Indicator(s)	Hazard type	Source
settlement/ infrastructure sensitivity		population at flood risk from sea level rise	G	[31], p.66, 97
health				
inadequate health care facilities and supplies			G	[332], p.42
health and sanitation		average calorie supply per capita	G	[217], p.2
		%age of people with access to adequate sanitation	G	[217], p.2
		%age of people with access to safe water / improved water supply (total, urban, rural)	G D	[217], p.2 [333], p.102 [243], p.67
		number of physicians (per 1000 inhabitants)	G F	[217], p.2 [333], p.102
		number hospital beds	G F	[217], p.2 [333], p.102
		life expectancy at birth for both sexes	G F	[217], p.2 [333], p.102
		under five year old mortality rate	G D	[217], p.2 [333], p.102
hygiene		access to drinking water	F D C	[237], p.90ff

Factor	Sub-factor	Indicator(s)	Hazard type	Source
		quality of sewage system	F D C	[237], p.90
population				
population growth and density/ density level		residents / km^2	G F C	[166], p.193 [332], p.42 [383], p330 [195], p.182ff [333], p.102
(level of) urbanization, rural / urban		percent rural farm population, percent urban population	G F C	[166], p.193 [29], p.934 [67], p.243ff [186], p.19,27 [333], p.5 [243], p.67
urban growth			F D C	[237], p.90
natural disaster				
proneness to natural disasters			G	[32], p.1617
frequency			G	[139], p.7
impact			G	[139], p.7
patterns (occurring)			G	[139], p.7
duration			G	[139], p.7

Factor	Sub-factor	Indicator(s)	Hazard type	Source
rate of relative sea-level rise		change in mean water elevation	G SL	[29], p.934 [309], p. risk variables [308], p.risk variables
shoreline erosion and accretion rates		meters / year	G SL	[29], p.934 [307], p.risk variables [309], p. risk variables [308], p.risk variables
beach erosion		changes in littoral profiles	CE	[29], p.933
beach reduction (destruction)			CE	[149], p.20
buoyancy			F	[59],p.16
mean wave height		meters	G SL	[29], p.934 [307], p.risk variables [309], p. risk variables [308], p.risk variables

Factor	Sub-factor	Indicator(s)	Hazard type	Source
inundation depth			F	[59], p.17
velocity		velocity-depth function is indicating if building collapse	F	[59], p.17f
hydrostatic pressure			F	[59], p.16
dynamic pressure			F	[59], p.16
duration of inundation			F	[59], p.17
mean tidal range		meters	G SL	[29], p.934 [307], p.risk variables [309], p. risk variables [308], p.risk variables
geophysical characteristics				
coastal slope		percent	G SL	[29], p.934 [307], p.risk variables [309], p. risk variables [308], p.risk variables
topography			G	[111], p.158

Factor	Sub-factor	Indicator(s)	Hazard type	Source
geomorphology (erodability)		ordinal value	G SL	[29], p.934 [307], p.risk variables [309], p. risk variables [308], p.risk variables
sediment concentration			F	[59], p.17
low-lying coasts			F SL C	[28], p.26
forest defensibility		forest areas slope, species flammability, forest accesses and fuel breaks	FF	[190], p.100f
preparedness				
availability and information content of flood warning			F	[59], p.17
quality of external response in a flood situation			F	[59], p.7
efficiency of protection works			G	[149], p.20
preparedness for floods		dams	F D C	[237], p.90

Factor	Sub-factor	Indicator(s)	Hazard type	Source
		legal regulations relating to floods	F D C	[237], p.90
critical buildings				
proliferation of nuclear reactors			G	[243], p.68
large dams			G	[243], p.68
high-rise buildings			G	[243], p.68
unsafe settlements		homes in hazard prone areas (ravines, river banks, etc.)	G	[25], p.267
building construction on man-made islands in coastal areas			G	[243], p.68
tourism				
more international travel			G	[243], p.68
housing				
housing conditions		share of population living in slums, proportion of semi-solid and fragile dwellings	G	[318], p.40 [243], p.64
structures		number of housing units (living quarters)	G	[25], p.267
degradation				
local environmental degradation		soil degradation / soil sealing, erosion	F D C	[237], p.91

Factor	Sub-factor	Indicator(s)	Hazard type	Source
land use / land cover				
constraints for agricultural use		soil, terrain, climate conditions regarding agricultural activities	F D C	[237], p.91
food security	cereals production / crop land area	degree of modernization in the agriculture sector, access of farmers to inputs to buffer against climate variability and change	G	[31], p.67,98
	protein consumption / capita	access to agricultural markets and other mechanisms (e.g., consumption shift) for compensating for shortfalls in production	G	[31], p.67,98
location				
location			G	[392], p.381
proximity to larger landmasses			OCHC	[28], p.26
remoteness of settlement			G	[332], 42 [243], 67f
location of dwelling		altitude (relating to sea level or local watersheds)	F D C	[237], 90ff
		terrain information (e.g. slope gradient)		[237], 90ff

Factor	Sub-factor	Indicator(s)	Hazard type	Source
mobility of assets				
mobility of assets (strategic retreat)			G	[149], 20

A.6 Factors in environmental vulnerability

Table A.50: Factors environmental vulnerability

Factor	Sub-factor	Indicator(s)	Hazard type	Source
land use / land cover				
arable land		land in farms as a percent of total land	G	[166], p.193 [29], p.934 [67], p.250
land cover			G	[111], p.193
land use / land cover		alpine / natural grassland, barren land, dam site, chir pine, landslide, settlement-agri-hoticulture, snow, temperate broadleaved / grassland and scrubs / conifers, mixed conifer, dumping site, river, continuous / discontinuous urban fabric, complex cultivation patterns, broad leaved / coniferous / mixed forest, water bodies	HW	[195], p.182ff [190], p.64f
area under forest		% of area of commune covered with forest	G	[25], p.277
vegetation cover		percentage of natural and regrowth vegetation cover remaining (forests, wetlands, prairies, tundra, desert and alpine associations)	G	[100]
land use	land cover		F D C	[237], p.91ff

Factor	Sub-factor	Indicator(s)	Hazard type	Source
natural impact	vegetation	vegetation type	G	[378], p.1932
ecosystems sensitivity		% land managed	G	[31], p.67
ecology	environmental stress	protected land area (%), forest change rate (% per year), % forest cover, unpopulated land area	G	[36], p.155 [1], p.82
quality of the environment		forests and woodland (in %age of land area)	G	[217], p.1
	irrigated land	%age of irrigated land	G D	[217], p.1 [163], p.32
natural disaster				
meteorological	sea (surface) temperature	(greatest) average annual deviation in surface sea temperature in last 5 years	ST	[161], p.16 [100]
	high winds	number of days over the last 5 years during which the max recorded wind speed (3 second gusts) > 20% higher than the average maximum for that month, average annual excess wind over the last five years	G E HWI S C T	[161], p.16 [121], p.4 [100]
	dry periods	number of month/ average annual rainfall deficit (mm) over the last 5 years during which rainfall > 20% lower than the 30yr average for that month	G D DP	[161], p.17 [121], p.4 [100]

Factor	Sub-factor	Indicator(s)	Hazard type	Source
	wet periods	number of month / average annual excess rainfall (mm) over the last 5 years during which rainfall $>$ 20% higher than the 30yr average for that month	G F W E	[161], p.16 [121], p.4 [100]
	heat waves, hot periods	number of days over the last 5 years during which the max temperature $\geq$ 5°C higher than the mean monthly maximum for that month, relative air humidity, number of (combined) heat days and tropical nights, number of heat waves, maximum air temperature	G HW HP DE TS	[161], p.16 [121], p.4 [100] [190], p.118
	cold snaps, cold periods	number of days / average annual heat deficit (degrees) over the last 5 years during which the max temperature $>$ 5°C lower than the mean monthly minimum for that month	G TS CP	[161], p.16 [121], p.4 [100]
climatological	forest fire, forest fire risk	land use / cover, forest canopy density, slope (degree), aspect, settlement, road, elevation	FF	[195], p.182ff
hydrological	slides, landslide susceptibility	number of slides recorded in the last 5 years, divided by land area	S	[100]
	flood risk	historical water marks, flood area, slope stability	G F	[383], p.330

Factor	Sub-factor	Indicator(s)	Hazard type	Source
sea-level rise	maximum wave height, shoreline erosion, accretion rate, land form susceptibility to inundation		SL	[29], p.933
flood risk			F	[383], p.330
risk related to the intensification of recurrent shocks	rainfall	level of rainfall	G	[123], p.523
		trend of shock in rainfall	G	[123], p.524
	temperature	level of temperature	G	[123], p.525
		trend of shock in temperature	G	[123], p.526
	storms	storms intensity	G	[123], p.527
		change in storms intensity	G	[123], p.528
risk related to progressive shocks	flooding due to sea level rise or ice melting	share of flood areas	G	[123], p.529
		size of likely rise in sea level	G	[123], p.530
	increasing aridity	share of dry lands	G	[123], p.531
		trend in ratio rainfall / evapotranspiration	G	[123], p.532
salinization	of groundwater / soil		G	[149], p.20
environmental impact		soil erosion, mountain hazard, land desertification	G	[378], p.1932
ecological sensitivity	soil sensitivity	soil erosion sensitivity	G	[142], p.543

Factor	Sub-factor	Indicator(s)	Hazard type	Source
combined indicators like dew point temperature and the Heat-Index		percentage of impervious area, percentage of area with land surface temperature > 28°C	HW	[190], p.118
population				
population		total human population density (number per km^2 land area)	G	[100]
population growth		annual human population growth rate over the last 5 years	G	[100]
coastal settlements		density of people living in coastal settlements (i.e. with a city centre within 100km of any maritime or lake coast)	G C	[100]
social pressure		population density	G	[142], p.543
socio-economic exposure	of coasts	coastal population	G	[112], p.22
tourism				
tourists		average annual number of international tourists per km^2 land over the past 5 years	G	[100]
degradation				
natural resource depletion		extent of natural resource depletion	G	[392], p.381 [332], p.42
environmental factors	environmental degradation, resource depletion (pressure arising from economic developments, geographical and natural characteristics		G	[32], p.1618

Factor	Sub-factor	Indicator(s)	Hazard type	Source
resource / soil / environmental / country wide degradation, degradation process, degraded land		state of resource degradation, environmental degradation indicators, deforestation rate, percent of land area that is either severely or very severely degraded, river fragmentation, forest damage, % of area that is degraded/ eroded/ desertified	G F D C	[392], p.381 [332], p.42f [29], p.933 [237], p.91 [100] [190], p.36 [25], p.277
deforestation			G	[333], p.5 [243], p.65
loss of cover		net percentage change in natural vegetation cover over the last five years	G	[100]
overused land		% of agricultural land that is overused	G	[25], p.277
polluted environment			G	[332], p.43
over-cultivation			G	[243], p.65
clearance of mangrove forests			G	[243], p.65
quality of the environment		human induced soil degradation	G	[217], p.1
pesticides		average annual pesticides used as $kg/km^2/year$ over total land area over last 5 years	G	[100]
renewable water		average annual water usage as percentage of renewable water resources over the last 5 years	G	[100]

Factor	Sub-factor	Indicator(s)	Hazard type	Source
intensive farming		annual tonnage of intensively farmed animal products (includes aquaculture, pigs, poultry) produced over the last five years per square kilometre land area	G	[100]
vehicles		number of vehicles per square kilometre of land area	G	[100]
fertilisers		average annual intensity of fertiliser use over the total land area over the last 5 years	G	[100]
sulphur dioxide emissions		average annual SO_2 emissions over the last 5 years	G	[100]
environmental impact		vegetation degradation	G	[378], p.1932
drainage of wetlands			G	[243], p.65f
ecological sensitivity	soil sensitivity	soil contamination level	G	[142], p.543
natural-social pressure	resource pressure	habitat degradation	G	[142], p.543
ecosystems sensitivity		fertilizer use / cropland area	G	[31], p.67
ecosystems conservation		conservation of rare or representative habitats, permanent loss of 'natural' environment, loss of biodiversity	FF	[190], p.102
waste				

Factor	**Sub-factor**	**Indicator(s)**	**Hazard type**	**Source**
inappropriate forms of waste management (especially in densely populated and urban environments)			G	[332], p.42
waste production		average annual net amount of generated and imported toxic, hazardous and municipal wastes per square kilometre land area over the last 5 years	G	[100]
waste treatment		mean annual percent of hazardous, toxic and municipal waste effectively managed and treated over the past 5 years	G	[100]
infrastructure / access to resources				
sanitation		density of population without access to safe sanitation	G	[100]
reduced access to clean air, safe water / sanitation, usable water and access to drinking water / basic services		% of homes with piped drinking water	G	[332], p.42 [166], p.193 [25], p.276
biophysical sensitivity	of water, water resource sensitivity	current temperature, water resources per capita, GHG emissions, renewable supply and inflow, water use, calculated using ratio of available water used	G	[112], p.22 [31], p.67
	of food	current temperature, change in crop yields, GHG emissions	G	[112], p.22

Factor	Sub-factor	Indicator(s)	Hazard type	Source
socio-economic exposure	of water	water use ratio	G	[112], p.22
	of food	agricultural GDP and labor force	G	[112], p.22
natural resources		quality / availability of water resources, soil erosion, increasing pollution, time to recovery	FF	[190], p.102
geography and demography	resource pressure, infrastructure / disease	population density	G	[36], p.155 [1], p.82
ecology	sustainability of water resources	groundwater recharge per capita, water resources per capita	G	[36], p.155 [1], p.82
growing water scarcity			G	[332], p.43
geophysical characteristics				
physiognomy	physiognomy of investigated area, terrain characteristica		G	[383], p.328
relief, topography	slope / elevation	altitude range, slope (%)	G F D C	[100] [237], p. 91ff [378], p.1932
beach width			SL CE OCH EW	[213], p.1392

Factor	Sub-factor	Indicator(s)	Hazard type	Source
dune width			SL CE OCH EW	[213], p.1392
distance to 20m isobath			SL CE OCH EW	[213], p.1392
distance of vegetation behind the back beach			SL CE OCH EW	[213], p.1392
geological settings			G	[237], p.85
natural impact	soil	soil type and texture	G	[378], p.1932
forest canopy density (%)		= number of canopy hits / total number of steps *100	G	[195], p.182ff
percentage outcrop			SL CE OCH EW	[213], p.1392
regions characteristics				

Factor	**Sub-factor**	**Indicator(s)**	**Hazard type**	**Source**
lowlands		percentage of land area less than or equal to 50m above sea level	G F SL S	[100]
borders		number of land and sea borders shared with other countries	G	[100]
isolation		distance to nearest continent (km)	G	[100]
country dispersion		ratio of length of borders (land and maritime) to total land area	G FF C	[100]
limited land areas			FF C	[243], p.68
land area		total land area (km^2)	G	[100]
biophysical sensitivity	of coasts	share of coastal area	G	[112], p.22
geography and demography	coastal risk	km of coastline (scale by land area), population within 100km of coastline (%)	G	[36], p.155 [1], p.82
proximity to the forest and extensive razing areas		wildland urban interface characteristics, distance of each settlement to the forest, distance to extensive grazing areas	FF	[190], p.100f
biodiversity				
endemics		number of known endemic species per million square kilometre land area	G	[100]

Factor	**Sub-factor**	**Indicator(s)**	**Hazard type**	**Source**
introductions		number of introduced species per 1000 square kilometre of land area	G	[100]
endangered species		number of endangered and vulnerable species per 1000 sq km land area	G	[100]
extinctions		number of species known to have become extinct since 1900 per 1000 sq km land area	G	[100]
migrations		number of known species that migrate outside the territorial area at any time during their life spans / area of land	G	[100]
(loss of) biodiversity, diminish biodiversity, diversity	biological diversity	different types of species, different functional role of species	G	[166], p.193 [332], p.43 [243], p.65ff [124], p.3f
climate / climate change				
climate		climate records and their long-term changes, rainfall (mm/year), wind (days/year), temperature (accumulated temperature, $\geq 10°C$)	G	[237], p.85ff [378], p.1932
(sufferance from) climate change		significant change of measurable climate characteristics	G F D C	[237], p.91 [392], p.381
government / governance				

Factor	Sub-factor	Indicator(s)	Hazard type	Source
international political relations			G	[237], p.85
regional political stability, conflicts		number and intensity of regional conflicts, average number of conflict years per decade within the country over the past 50 years	G	[237], p.89 [100]
energy consumption				
industry		average annual use of electricity for industry over the last 5 years per square kilometre of land	G	[100]
environment				
environmental conditions			G	[111], p.158
stability of ecosystems			G	[166], p.193
ecological important areas		marine protected areas (#), bird sanctuary sites (#), estuary mouths (#), protected areas (terrestrial)	SL CE OCH EW	[213], p.1392
scarcity of ecosystem			G	[149], p.20
mobility of ecosystem			G	[149], p.20
regulations				
environmental agreements		number of environmental treaties in force in a country	G	[100]
terrestrial reserves		percent of terrestrial land area legally set aside as no take reserves	G	[100]

Factor	**Sub-factor**	**Indicator(s)**	**Hazard type**	**Source**
marine reserves		percentage of continental shelf legally designated as MPAs	G	[100]
human impact				
fishing effort		average annual number of fishers per kilometre of coastline over the last 5 years	G	[100]
hemeroby (natural distance)			G	[190], p. 36
environmental openness		average annual USD freight imports over the past 5 years by any means per km^2 land area	G	[100]
habitat fragmentation		total length of all roads in a country divided by land area	G	[100]
mining		average annual mining production per km^2 of land area over the past 5 years	G	[100]
ecological sensitivity	habitat sensitivity	habitat sensitivity	G	[142], p.543
natural-social pressure	economic pressure	enterprise distribution density	G	[142], p.543

A.7 Natural disaster types - definitions

Table A.64: Natural disaster types - definitions (extracted from[152], p.12ff and extended with [75], [92], [16], [15], [88])

Term	Definition
Airburst	An explosion of a comet or meteoroid within the Earth's atmosphere without striking the ground.
Animal Accident	Human encounters with dangerous or exotic animals in both urban and rural environments.
Ash fall	Fine (less than 4 mm in diameter) unconsolidated volcanic debris blown into the atmosphere during an eruption; can remain airborne for long periods of time and travel considerable distance from the source.
Avalanche	A large mass of loosened earth material, snow, or ice that slides, flows or fall rapidly down a mountainside under the force of gravity. Snow Avalanche: Rapid downslope movement of a mix of snow and ice. Debris Avalanche: The sudden and very rapid downslope movement of unsorted mass of rock and soil. There are two general types of debris avalanches - a cold debris avalanche usually results from an unstable slope suddenly collapsing whereas a hot debris avalanche results from volcanic activity leading to slope instability and collapse.
Bacterial disease	An unusual increase in the number of incidents caused by the exposure to bacteria either through skin contact, ingestion or inhalation. Examples include salmonella, MSRA, and cholera, among others.
Coastal flood	Higher-than-normal water levels along the coast caused by tidal changes or thunderstorms that result in flooding, which can last from days to weeks.
Cold wave	A period of abnormally cold weather. Typically a cold wave lasts two or more days and may be aggravated by high winds. The exact temperature criteria for what constitutes a cold wave vary by location.
Convective storm	A type of meteorological hazard generated by the heating of air and the availability of moist and unstable air masses. Convective storms range from localised thunderstorms (with heavy rain and/or hail, lightning, high winds, tornadoes) to meso-scale, multi-day events.
Debris, Mudflow, Rockfall	Types of landslides that occur when heavy rain or rapid snow/ice melt send large amounts of vegetation, mud, or rock downslope by gravitational forces.
Derecho	Widespread and usually fast-moving windstorms associated with convection/convective storm. Derechos include down-burst and straight-line winds. The damage from derechos is often confused with the damage from tornadoes.
Disease	an infectious disease that already existed in the region (e.g., flu, E. coli) or the appearance of an infectious disease previously absent from the region (e.g., plague, polio).

Term	Definition
Drought	An extended period of unusually low precipitation that produces a shortage of water for people, animals and plants. Drought is different from most other hazards in that it develops slowly, sometimes even over years, and its onset is generally difficult to detect. Drought is not solely a physical phenomenon because its impacts can be exacerbated by human activities and water supply demands. Drought is therefore often defined both conceptually and operationally. Operational definitions of drought, meaning the degree of precipitation reduction that constitutes a drought, vary by locality, climate and environmental sector.
Earthquake	Sudden movement of a block of the Earth's crust along a geological fault and associated ground shaking.
Energetic particels	Emissions from solar radiation storms consisting of pieces of matter (e.g., protons and other charged particles) moving at very high speed. The magnetosphere and atmosphere block (solar) energetic particles (SEP) from reaching humans on Earth but they are damaging to the electronics of space-borne technology (such as satellites) and pose a radiation hazard to life in space and aircrafts travelling at high altitudes.
Epidemic	Either an unusual increase in the number of cases of an infectious disease, which already exists in the region or population concerned; or the appearance of an infection previously absent from a region.
Extratropical storm	A type of low-pressure cyclonic system in the middle and high latitudes (also called mid-latitude cyclone) that primarily gets its energy from the horizontal temperature contrasts (fronts) in the atmosphere. When associated with cold fronts, extratropical cyclones may be particularly damaging (e.g., European winter/windstorm, Nor'easter).
Extreme temperature	A general term for temperature variations above (extreme heat) or below (extreme cold) normal conditions.
Flash flood	Heavy or excessive rainfall in a short period of time that produce immediate runoff, creating flooding conditions within minutes or a few hours during or after the rainfall.
Flood	A general term for the overflow of water from a stream channel onto normally dry land in the floodplain (riverine flooding), higher-than normal levels along the coast and in lakes or reservoirs (coastal flooding) as well as ponding of water at or near the point where the rain fell (flash floods).
Fog	Water droplets that are suspended in the air near the Earth's surface. Fog is simply a cloud that is in contact with the ground.
Forest fire	A type of wildfire in a wooded area.

Term	Definition
Frost, Freeze	Frost is the consequence of radiative cooling resulting in the formation of thin ice crystals on the ground or other surfaces in the form of needles, feathers, scales, or fans. Frost occurs when the temperature of surfaces is below freezing and water vapor from humid air forms solid deposits on the cold surface. Freeze occurs when the air temperature is at $(32 \circ F/0 \circ C)$ or below over a widespread area for a climatologically significant period of time. Use of the term is usually restricted to advective situations or to occasions when wind or other conditions prevent frost. Frost and freeze are particularly damaging during the crop growing season.
Fungal disease	Exposure to fungi either through skin contact, ingestion or inhalation of spores resulting in an unusual increase in the number of incidents. Examples are fungal pneumonia, fungal meningitis, etc.
Geomagnetic storm	A type of extraterrestrial hazard caused by solar wind shockwaves that temporarily disturb the Earth's magnetosphere. Geomagnetic storms can disrupt power grids, spacecraft operations, and satellite communications.
Glacial lake outburst	A flood that occurs when water dammed by a glacier or moraine is suddenly released. Glacial lakes can be at the front of the glacier (marginal lake) or below the ice sheet (sub-glacial lake).
Ground shaking	General term referring to the qualitative or quantitative aspects of movement of the Earth's surface from earthquakes or explosions. Ground motion is produced by waves that are generated by sudden slip on a fault or sudden pressure at the explosive source and travel through the Earth and along its surface.
Hail	Solid precipitation in the form of irregular pellets or balls of ice more than 5 mm in diameter.
Heat wave	A period of abnormally hot and/or unusually humid weather. Typically a heat wave lasts two or more days. The exact temperature criteria for what constitutes a heat wave vary by location.
Ice jam flood	The accumulation of floating ice restricting or blocking a river's flow and drainage. Ice jams tend to develop near river bends and obstructions (e.g., bridges).
Impact	A type of extraterrestrial hazard caused by the collision of the Earth with a meteoroid, asteroid or comet.
Insect infestation	The pervasive influx, swarming and/or hatching of insects affecting humans, animals, crops, and perishable goods. Examples are locusts and African Bees.
Lahar	Hot or cold mixture of earthen material flowing on the slope of a volcano either during or between volcanic eruptions.

Term	Definition
Landfire: brush, bush, pasture	Grassfires are fast moving, passing in five to ten seconds and smouldering for minutes. They have a low to medium intensity and primarily damage crops, livestock and farming infrastructure, such as fences. Bushfires are generally slower moving, but have a higher heat output. This means they pass in two to five minutes, but they can smoulder for days. Fire in the crown of the tree canopy can move rapidly.
Landslide	The failure and movement of a mass of rock, sediment, soil, or artificial fill under the influence of gravity.
Lava flow	The ejected magma that moves as a liquid mass downslope from a volcano during an eruption.
Lightning	A high-voltage, visible electrical discharge produced by a thunderstorm and followed by the sound of thunder.
Locust	Locusts are a type of insect that can be devastating pests of agriculture due to their ability to develop very large populations and to form dense and highly mobile swarms.
Mass movement	Any type of downslope movement of earth materials.
Parasitic disease	Exposure to a parasite–an organism living on or in a host–causes an unusual increase in the number of incidents. Exposure to parasites occurs mostly through contaminated water, food or contact with insects, animals (zoonotic), pets, etc. Examples are malaria, chagas disease, giardiasis and trichinellosis.
Prion disease	A type of biological hazard caused by prion proteins. Prion diseases or transmissible spongiform encephalopathies (TSEs) are a family of rare progressive neurodegenerative disorders that affect both humans and animals characterised by long incubation periods and neural loss. Examples are Bovine Spongiform Encephalophathy (BSE), Creutzfeldt-Jakob-Disease (CJD), Kuru, etc.
Pyroclastic flow	Extremely hot gases, ash, and other materials of more than 1,000 degrees Celsius that rapidly flow down the flank of a volcano (more than 700 km/h) during an eruption.
Rain	Water vapour condenses in the atmosphere to form water droplets that fall to the Earth.
Riverine flood	A type of flooding resulting from the overflow of water from a stream or river channel onto normally dry land in the floodplain adjacent to the channel.
Rogue Wave	An unusual single crest of an ocean wave far out at sea that is much higher and/or steeper than other waves in the prevailing swell system.
Sand, Dust storm	Strong winds carry particles of sand aloft, but generally confined to less than 50 feet (15 m), especially common in arid and semi-arid environments. A dust storm is also characterised by strong winds but carries smaller particles of dust rather than sand over an extensive area.

Term	Definition
Seiche	A standing wave of water in a large semi- or fully-enclosed body of water (lakes or bays) created by strong winds and/or a large barometric pressure gradient.
Severe winter conditions	Damage caused by snow and ice. Winter damage refers to damage to buildings, infrastructure, traffic (esp. navigation) inflicted by snow and ice in form of snow pressure, freezing rain, frozen waterways etc.
Snow, Ice	Precipitation in the form of ice crystals/snowflakes or ice pellets (sleet) formed directly from freezing water vapour in the air. Ice accumulates when rain hits the cold surface and freezes.
Space weather	Weather A general term for extraterrestrial weather conditions driven by solar eruptions such as geomagnetic storms, radio disturbances, and solar energetic particles.
Storm	Tropical storms, cyclones, hurricanes and typhoons, although named differently, describe the same disaster type. Essentially, these disaster types refer to a large scale closed circulation system in the atmosphere which combines low pressure and strong winds that rotate counter clockwise in the northern hemisphere and clockwise in the southern hemisphere.
Surge	A long lasting increase in water level.
Tornado	A violently rotating column of air that reaches the ground or open water (waterspout).
Tropical storm	A tropical storm originates over tropical or subtropical waters. It is characterised by a warm-core, non-frontal synoptic-scale cyclone with a low pressure centre, spiral rain bands and strong winds. Depending on their location, tropical cyclones are referred to as hurricanes (Atlantic, Northeast Pacific), typhoons (Northwest Pacific), or cyclones (South Pacific and Indian Ocean).
Tsunami	A series of waves (with long wavelengths when traveling across the deep ocean) that are generated by a displacement of massive amounts of water through underwater earthquakes, volcanic eruptions or landslides. Tsunami waves travel at very high speed across the ocean but as they begin to reach shallow water they slow down and the wave grows steeper.
Volcanic activity	A type of volcanic event near an opening/vent in the Earth's surface including volcanic eruptions of lava, ash, hot vapour, gas, and pyroclastic material.
Wave action	Wind-generated surface waves that can occur on the surface of any open body of water such as oceans, rivers and lakes, etc. The size of the wave depends on the strength of the wind and the traveled distance (fetch).

Term	Definition
Wildfire	Any uncontrolled and non-prescribed combustion or burning of plants in a natural setting such as a forest, grassland, brush land or tundra, which consumes the natural fuels and spreads based on environmental conditions (e.g., wind, topography). Wildfires can be triggered by lightning or human actions.
Wind	Differences in air pressure resulting in the horizontal motion of air. The greater the difference in pressure, the stronger the wind. Wind moves from high pressure toward low pressure.
Winter storm / Blizzard	A low pressure system in winter months with significant accumulations of snow, freezing rain, sleet or ice. A blizzard is a severe snow storm with winds exceeding 35 mph (56 km/h) for three or more hours, producing reduced visibility (less than .25 mile (400 m).

A.8 Business closure times

Table A.70: Business closure times (complete)

ID	EventID	% businesses closed within interval	Interval start [days]	Interval end [days]	Interval center	Mean	Source
1	1	0.245	0	0	0	0	[382]
1	1	0.446	0.042	3	1.52	0.019	[382]
1	1	0.195	4	7	5.5	0.78	[382]
1	1	0.074	8	21	14.5	0.592	[382]
1	1	0.04	22	inf	365	14.6	[382]
2	1	0.249	0	0	0	0	[379]
2	1	0.751	8	8	8	6.008	[379]
3	2	0.099	0	0	0	0	[382]
3	2	0.116	0.042	3	1.52	0.005	[382]
3	2	0.183	4	7	5.5	0.732	[382]
3	2	0.253	8	21	14.5	2.024	[382]
3	2	0.349	22	inf	365	127.385	[382]
4	2	0.1	0	0	0	0	[379]
4	2	0.9	64	64	64	57.6	[379]
5	3	0.491	0	0	0	0	[385]
5	3	0.082	2	2	2	0.164	[385]
5	3	0.077	3	3	3	0.2295	[385]
5	3	0.025	4	4	4	0.0984	[385]
5	3	0.063	5	5	5	0.314	[385]
5	3	0.077	8	8	8	0.612	[385]
5	3	0.079	9	9	9	0.7128	[385]
5	3	0.107	11	11	11	1.1726	[385]
5	3	0.081	0.041	0.958	0.5	0.003	[158]
6	3	0.18	1	1	1	0.18	[158]
6	3	0.11	2	2	2	0.22	[158]
6	3	0.06	3	3	3	0.18	[158]
6	3	0.09	4	4	4	0.36	[158]
6	3	0.144	5	5	5	0.72	[158]
6	3	0.015	6	6	6	0.09	[158]
6	3	0.11	7	7	7	0.77	[158]
6	3	0.11	14	14	14	1.54	[158]

6	3	0.05	21	21	21	1.05	[158]
6	3	0.015	28	28	28	0.42	[158]
6	3	0.035	inf	inf	365	12.775	[158]
7	4	0.629	0	0	0	0	[8]
7	4	0.371	42.556	42.583	42.570	15.801	[8]
8	5	0.24	0	0	0	0	[53]
8	5	0.5	0.042	1	0.521	0.021	[53]
8	5	0.2	7	7	7	1.4	[53]
8	5	0.06	182.5	304.167	243.333	10.95	[53]
9	6	0.354	36	36	36	12.751	[170]
9	6	0.386	52	52	52	20.046	[170]
9	6	0.142	48	48	48	6.826	[170]
9	6	0.101	30	30	30	3.036	[170]
9	6	0.017	18	18	18	0.304	[170]
10	6	0.91	14	14	14	12.74	[87]
10	6	0.09	0	0	0	0	[87]
11	7	1	15.208	60.833	38.021	15.208	[61]
12	7	0.127	0	0	0	0	[173]
12	7	0.197	3	3	3	0.592	[173]
12	7	0.333	94	94	94	31.283	[173]
12	7	0.095	184	184	184	17.48	[173]
12	7	0.037	267	267	267	9.826	[173]
12	7	0.041	368	368	368	14.904	[173]
12	7	0.046	763	763	763	35.403	[173]
12	7	0.124	inf	inf	365	45.151	[173]
13	7	0.75	28,4	28,4	28.4	21.3	[297]
13	7	0.25	inf	inf	365	91.25	[297]
14	7	0.446	0	91.25	45.625	0	[175]
14	7	0.186	92.25	182.5	137.375	17.131	[175]
14	7	0.079	183.5	365	274.25	14.460	[175]
14	7	0.290	366	inf	365	105.741	[175]
15	8	0.59	0	0	0	0	[314]
15	8	0.41	3	4	3.5	1.23	[314]
16	9	0.259	0	0	0	0	[223]
16	9	0.070	0.042	1	0.521	0.003	[223]
16	9	0.014	2	3	2.5	0.028	[223]
16	9	0.004	4	7	5.5	0.014	[223]

16	9	0.004	8	21	14.5	0.028	[223]
16	9	0.650	22	inf	365	237.360	[223]
17	10	0.719	0	0	0	0	[23]
17	10	0.095	3.33	3.33	3,33	0.316	[23]
17	10	0.079	27.89	27.89	27.89	2.195	[23]
17	10	0.107	11.24	11.24	11.24	1.206	[23]
18	10	0.622	1.51	inf	365	227.03	[235]
18	10	0.378	0	1.5	0.75	0	[235]
19	10	0.56	2	2	2	1.12	[315]
19	10	0.44	0	0	0	0	[315]
20	11	0.173	7	30.417	18.708	1.211	[7]
20	11	0.47	38.021	98.854	68.438	17.870	[7]
20	11	0.203	106.458	167.292	136.875	21.611	[7]
20	11	0.05	174.896	266.146	220.521	8.745	[7]
20	11	0.104	inf	inf	365	37.96	[7]
21	12	0.02	0	0	0	0	[215]
21	12	0.01	7.604	7.604	7.604	0.076	[215]
21	12	0.04	15.208	15.208	15.208	0.608	[215]
21	12	0.01	22.813	22.813	22.813	0.228	[215]
21	12	0.145	30.417	30.417	30.417	4.410	[215]
21	12	0.025	45.625	45.625	45.625	1.141	[215]
21	12	0.27	60.833	60.833	60.833	16.425	[215]
21	12	0.17	91.25	91.25	91.25	15.513	[215]
21	12	0.01	94.292	94.292	94.292	0.943	[215]
21	12	0.01	106.458	106.458	106.458	1.065	[215]
21	12	0.05	121.667	121.667	121.667	6.083	[215]
21	12	0.045	152.083	152.083	152.083	6.844	[215]
21	12	0.145	182.5	182.5	182.5	26.463	[215]
21	12	0.005	304.167	304.167	304.167	1.521	[215]
21	12	0.005	334.583	334.583	334.583	1.673	[215]
21	12	0.03	365	365	365	10.95	[215]
21	12	0.01	366	inf	365	3.65	[215]
22	12	0.017	241	241	241	4.025	[128]
22	12	0.036	236	236	236	8.449	[128]
22	12	0.030	232	232	232	6.914	[128]
22	12	0.014	231	231	231	3.303	[128]
22	12	0.068	228	228	228	15.481	[128]

22	12	0.011	225	225	225	2.408	[128]
22	12	0.074	inf	inf	365	26.974	[128]
22	12	0.751	0	225	112.5	0	[128]
23	13	0.03	30.417	inf	365	10.95	[51]
23	13	0.05	21	30	25.5	1.05	[51]
23	13	0.09	11	20	15.5	0.99	[51]
23	13	0.14	6	10	8	0.84	[51]
23	13	0.36	3	5	4	1.08	[51]
23	13	0.15	1	2	1.5	0.15	[51]
23	13	0.18	0	0	0	0	[51]
24	13	1	30.417	30.417	30.417	30.417	[396]
25	14	0.01	0	0	0	0	[52]
25	14	0.548	0.042	5	2.521	0.023	[52]
25	14	0.221	6	10	8	1.326	[52]
25	14	0.135	11	20	15.5	1.485	[52]
25	14	0.019	21	30	25.5	0.399	[52]
25	14	0.029	30.417	60.833	45.625	0.882	[52]
25	14	0.01	91.25	152.083	121.667	0.913	[52]
25	14	0.029	182.5	inf	365	10.585	[52]
26	15	0.023	6.54	6.54	6.54	0.151	[40]
26	15	0.031	9.94	9.94	9.94	0.306	[40]
26	15	0.012	12.92	12.92	12.92	0.149	[40]
26	15	0.668	0	0	0	0	[40]
26	15	0.023	12.96	12.96	12.96	0.299	[40]
26	15	0.004	1	1	1	0.004	[40]
26	15	0.012	8.58	8.58	8.58	0.099	[40]
26	15	0.015	16.75	16.75	16.75	0.258	[40]
26	15	0.065	10.74	10.74	10.74	0.702	[40]
26	15	0.047	8.02	8.02	8.02	0.378	[40]
26	15	0.004	5	5	5	0.019	[40]
26	15	0.05	6.31	6.31	6.31	0.316	[40]
26	15	0.008	2	2	2	0.015	[40]
26	15	0.039	0.83	0.83	0.83	0.032	[40]
27	16	0.023	104.46	104.46	104.46	2.413	[40]
27	16	0.0308	89.03	89.03	89.03	2.742	[40]
27	16	0.012	23.25	23.25	23.25	0.267	[40]
27	16	0.004	51.75	51.75	51.75	0.197	[40]

27	16	0.023	34.25	34.25	34.25	0.791	[40]
27	16	0.004	42.5	42.5	42.5	0.162	[40]
27	16	0.012	31.58	31.58	31.58	0.363	[40]
27	16	0.015	13.13	13.13	13.13	0.202	[40]
27	16	0.065	11.72	11.72	11.72	0.766	[40]
27	16	0.046	14.27	14.27	14.27	0.659	[40]
27	16	0.004	14	14	14	0.053	[40]
27	16	0.005	14.35	14.35	14.35	0.072	[40]
27	16	0.077	12.38	12.38	12.38	0.953	[40]
27	16	0.039	21.35	21.35	21.35	0.8220	[40]
27	16	0.641	0	0	0	0	[40]
28	17	0.023	32.21	32.21	32.21	0.744	[40]
28	17	0.031	17.78	17.78	17.78	0.548	[40]
28	17	0.012	27.08	27.08	27.08	0.311	[40]
28	17	0.004	6.25	6.25	6.25	0.024	[40]
28	17	0.023	6.33	6.33	6.33	0.146	[40]
28	17	0.004	4	4	4	0.015	[40]
28	17	0.012	4.92	4.92	4.92	0.057	[40]
28	17	0.015	14.56	14.56	14.56	0.224	[40]
28	17	0.065	8.24	8.24	8.24	0.539	[40]
28	17	0.0462	4.19	4.19	4.19	0.194	[40]
28	17	0.004	5	5	5	0.019	[40]
28	17	0.05	2.88	2.88	2.88	0.144	[40]
28	17	0.008	8.75	8.75	8.75	0.067	[40]
28	17	0.039	0.6	0.6	0.6	0.023	[40]
28	17	0.665	0	0	0	0	[40]
29	18	0.88	15.208	15.208	15.208	13.383	[306]
29	18	0.12	0	0	0	0	[306]
30	19	1	15.208333	15.208	15.208	15.208	[219]
31	20	0.043	38.021	38.021	38.021	1.620	[179] [293] [317]
31	20	0.006	365	365	365	2.081	[179] [293] [317]
31	20	0.01	inf	inf	365	3.65	[179] [293] [317]

31	20	0.0003	8	8	8	0.002	[179] [293] [317]
31	20	0.0003	40	40	40	0.011	[179] [293] [317]
31	20	0.941	0	0	0	0	[179] [293] [317]
32	21	1	182.5	182.5	182.5	182.5	[27]

A.9 Vulnerability indicator USA 1989

Table A.71: Values vulnerability factors USA 1989

Indicator	Value
% unemployed	6.946153846
%age of rural population	0.24911
%age of urban population	0.752095141
GDP per capita (current US$)	22922.43709
R&D investment (% GDP)	2.144146842
access to electricity (% total population)	100
access to improved sanitation facilities (% total population)	99.5
access to improved water source (% total population)	98.4
agricultural irrigated land (% of total agricultural land)	5.377644
agriculture (% of GDP)	1.407243976
arable land (% of total area)	20.27806651
arable land (in hectars)	185726000
birth rate (number of birth per 1000 population)	16.4
coastlines in km	19924
education expenditure as % of GNP (here GDP)	4.3
energy imports, net (% of energy use)	16.9955043
exports of goods and services (% of GDP)	8.913368046
female per percentage of population	50.97927927
food imports (% of merchandise imports)	5.718647562
forest area (% of land area)	33.02230821
gross national product (GNI)	5.6183E+12
housing units per square mile	28.90848893
imports of goods and services (% of GDP)	10.44651946
km of coastline (scale by land area)	0.002174651
labor force	128187674
labour force with primary education	20.47647059
labour force with secondary education	50.12183411
labour force with tertiary education	32.62352941
land area in square miles	3537438.44
land area where elevation is below 5 meters (% of total land area)	1.167679223
length of land and sea borders shared with other countries (km)	12048
marine protected areas (% of total area)	22.6

median age	32.9
number of housing units	102262000
number of land and sea borders shared with other countries	2
number of physicians per 1,000 population	1.8
ores and metals imports (% of merchandise imports)	3.149024483
percent of population above 65	12.43866546
percent of population participating in the labour force	0.51935902
percent of population under 5	9
population	246819000
population living in areas where elevation is below 5 meters (% of total population)	2.574566261
public expenditure on health as per cent of GDP	5.160893142
railways in km	200380.645
ratio of length of borders (land and maritime) to total land area	0.001315007
researchers in R&D per million population	2753.527011
road density (km of road per land area km^2)	0.680928964
roadways in km	6238623.625
rural land area where elevation is below 5 meters (% of total land area)	0.980329212
rural population	61485081
rural population living in areas where elevation is below 5 meters (% of total population)	0.245736835
terrestrial protected areas (% of total area)	13.7
total human population density (persons/km^2) / square mile	26.94836532
total land area (km2)	9161930.185
urban land area where elevation is below 5 meters (% of total land area)	0.187350011
urban population	187053487
urban population living in areas where elevation is below 5 meters (% of total population)	2.328829426
waterways in km	123700

A.10 Sources vulnerability indicator

Table A.72: Sources vulnerability indicator

Region	Sources
Australia	[304]; [50]; [13]; [11]; [9]; [14]; [10]; [12]; [13]
Canada	[304]; [50];[281]; [278]; [279]; [280]; [44]
Germany	[304]; [50]; [272]; [37]; [254]; [288]; [290]; [287]; [289]; [286]
New Zealand	[304]; [50]; [150]; [291]; [282]; [185]
Pakistan	[304]; [50]; [267]; [211]; [212]; [209]; [210]; [208]; [267]
South Africa	[304]; [50]; [284]; [285]; [283]; [270]; [334]; [270]; [222]; [105]; [85]; [337]; [246]
Thailand	[304]; [50]; [200]; [199]; [198]; [197]; [271]; [335]; [271]; [104]
USA	[304]; [50]; [341]; [338]; [354]; [363]; [352]; [249]; [259]; [251]; [258]; [274]; [360]; [266]; [261]; [264]; [340]; [39]; [339]; [342]; [368]; [262]; [263]; [261]; [264]; [250]; [357]; [365]; [358]; [368]; [256]; [355]; [364]; [351]; [346]; [253]; [252]; [356]; [255]; [361]; [367]; [265]; [359]; [366]; [274]; [257]; [263]; [275]; [260]; [250]; [348]; [350]; [349]; [344]; [345]; [347]; [339]; [321]; [342]; [353]; [362]; [369]; [5]; [329]; [328]; [327]; [326]; [325]; [324]; [331]; [330]; [342]; [322]; [323]
United Kingdom	[304]; [50]; [268]; [269]; [276]; [273]; [83]; [302]; [83]; [82]; [84]; [81]

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