Criticality of infrastructure networks under consideration of resilience-based maintenance strategies using the example of inland waterways

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

von

M.Sc. Rebecca Wehrle
geb. in Freiburg im Breisgau

Tag der mündlichen Prüfung:	12.12.2022
Hauptreferent:	Prof. Dr. Frank Schultmann
Korreferent:	Prof. Dr. Marcus Wiens

Abstract

Transportation infrastructures as backbone of modern, globalized, and networked societies ensure flows of people and goods and thus sustain social and economic prosperity. Concurrently, more and more infrastructure construction assets are facing the problem of systematic obsolescence due to deficient structural conditions, maintenance backlogs, and a lack of or misallocation of resources for the construction and maintenance of infrastructure buildings. This problem construct necessitates a resilience-based maintenance strategy for the asset portfolio. In particular, inland navigation as a mode of transport features large transport volumes and few redundancies. Combined with its increasing importance due to its comparatively high environmental friendliness, a predestined, yet in the literature underrepresented research subject results.

This dissertation aims to investigate essential factors of infrastructure management and thereby identify the potential for improvement in the complex construct of maintenance management and related areas. The emphasis is on enhancing the resilience of inland waterways as a complex System-of-Systems with all its interdependencies. Thus, a holistic risk and resilience assessment is essential and is underlined with the aspects *infrastructure availability and business decisions* (Study A, B, C and D) and *stakeholder communication and risk analysis* (Study E, F, G) which are addressed by seven studies published as companion articles.

Study A deals with assessing the reliability of transport infrastructure networks as part of supply chains, highlighting the importance of available and thus maintained infrastructure assets for functioning supply chains. Study B aims to identify critical warning times before closures of transport infrastructure networks and therefore suggests a mixed-methods approach, making it possible to derive and evaluate critical thresholds. Study C examines the corresponding company decisions, i.e., decisions as reaction towards neglected maintenance of public transport infrastructure, which comprises risk coping strategies, examined by empirical investigations. Study D extends this problem observation by showing that companies could see incentives for outsourcing if they face a lack of access to available transport infrastructure. Hence, the study analyzes facility relocation problems in dependence on infrastructure availability.

Study E heads toward stakeholder communication and risk analysis and examines the processes across stakeholders, using an approach of collaborative serious gaming, which simultaneously enhances situation awareness and communication among stakeholders. Study F provides the implementation of a systemic approach and its visualization as a GIS-based risk dashboard, shedding light on interdependencies among critical infrastructures and cascading effects. Study G closes with an examination of the evaluation of the potential of infrastructure funds. For this purpose, the study conducts an online survey to determine investors' willingness to pay for various fund mechanisms, integrating the option of private coverage.

Despite the geographic focus of the case studies on Germany, valuable insights can be gained for infrastructure management that can also apply to other countries. In addition to the case study findings, general recommendations for infrastructure owners are derived. As a result, it can be stated that it is essential that maintenance strategies have to be more resilience-based than traditional strategies, which are mainly based on fixed time intervals for maintenance. Moreover, the application of both serious gaming and GIS visualization can help to enhance situation awareness and thus the resilience of infrastructure systems. An essential finding for which this dissertation provides methodological approaches is that considering the local area's attractiveness for business locations should receive more attention regarding investment decisions. Thereby a focus should be set on the realistic threat of relocations as response to deteriorating infrastructure conditions. Eventually, public debates should strengthen the knowledge about infrastructure and its funding, while deficits in alongside mechanisms in infrastructure funding must be encountered.

Consequently, this dissertation provides insights into the potential of infrastructure management. Mainly, it offers the potential to improve the resilience of the waterway transportation system and address stakeholders accordingly.

Contents

Abbreviations

CI	Critical Infrastructure
GIS	Geographic Information System
IW	Inland Waterway
IWT	Inland Waterway Transport
PC	Private Coverage
PPP	Public-Private Partnership
SC	Supply Chain
SoS	System-of-Systems
TCO	Total Cost of Ownership
TPP	Traveling Purchaser Problem
UML	Unified Modeling Language
WCGN	West German Canal Network
WTP	Willingness to pay

List of Figures

List of Tables

Part I

Framework, Foundations and Implications

1 Introduction and Motivation

Inland Waterways (IWs) occupy a unique role in the system of interconnected infrastructure networks: Characterized by large cargo units, they link cities and companies via ports, thus constituting a vital transport infrastructure based on a large stock of buildings consisting of locks, weirs, and canal bridges, among others (Federal Ministry for Digital and Transport, 2015). Meanwhile, the condition of infrastructure building stocks is steadily deteriorating, while a systemic maintenance backlog and lacking or misallocated resources pose closely linked problems all over the world (Frangopol and Liu, 2007). Trechow (2011) and Ministerium für Bauen, Wohnen Stadtentwicklung und Verkehr des Landes Nordrhein-Westfalen (2016) e.g. shed light on the problem constellation in German waterways. Moreover, the systemic nature of these problems and the long duration and high demand for maintenance measures leave little hope of rapid recovery in the condition of the structures.

Progressing condition deterioration of IWs causes a reduction of resilience and thus reliability and availability of the infrastructure, leading to risks for concerned manufacturing industries. Progressive substance depletion can seriously endanger business locations and the mobility of the population (Behrendt and Trojahn, 2013). Moreover, IWs even inherit a potential threat to life and limb that can occur in the event of a failure. Meanwhile, the importance of infrastructure only enters the public consciousness when functionality is limited, yet impairments cannot be remedied in the short term (Daehre, 2012). Thus, a resilience-based maintenance strategy must consider all possible consequences to mitigate risks arising from deteriorating infrastructure assets. Resilience-based thereby addresses the system's resilience as its ability to absorb risks and recover from negative impacts of disruptive events (Gaillard, 2010), while criticality describes the possible negative consequences of such events (Lenz, 2009).

The application of findings from scientific studies that aim to support the resilience of transport infrastructure and its interdependencies with diverse stakeholders is exceptionally challenging. An elementary reason is that maintenance and construction as public tasks depend highly on scarce personnel resources and mostly routinely scheduled maintenance work. Stakeholders namely are the government, represented by the public sector and executive authorities, industrial stakeholders as well as the population, as section 2.2.3 sheds light on. Thus, barriers within internal and external stakeholder processes often prevent the implementation of system-wide, resilience-based maintenance strategies. At the same time, companies and the population are also interested in an intact infrastructure but have hardly any influence.

This dissertation aims to evaluate how transportation risks arising from deteriorating and disrupted transport infrastructure can be assessed, mitigated, and communicated. In this context, understanding company decisions as a reaction to infrastructure conditions is particularly crucial since risk communication among stakeholders plays an essential role in enhancing a system's resilience. For this purpose, measurements and communication options regarding the criticality of transport infrastructure systems are examined under consideration of two essential aspects:

(1) the significance of transport infrastructure for business locations
(2) the diverse character of different stakeholders regarding the little-studied example of waterways.

The present dissertation aspires to enable an increase in resilience with the help of seven studies addressing case studies located in the German infrastructure management, focusing on IWs. These studies assess different decisions across the IW infrastructure as complex System-of-Systems (SoS) (Eusgeld et al., 2011) which constitute unique challenges due to their complex interdependencies along with potential cascading effects (Buldyrev et al., 2010). Additional challenges in analyzing infrastructures relate to the importance of precise data collection and processing. It is demonstrated how empirical studies and scenario analyses can contribute to the efficient use of available data and how to generate new, required data in a targeted manner.

Thus, this work is structured according to Figure 1.1 along with the described problem fields *availability and company decisions* and *risk communication and stakeholder analysis*. Namely, the interplay of infrastructure availability and company decisions is addressed by four studies concerning availability assessment of infrastructure networks, notification time advancing asset closures, company decisions under consideration of infrastructure availability, and the potential relocation of firms as a reaction to deteriorating infrastructure conditions. The second part of the main contributions concerns risk communication and stakeholder analysis: It comprises an approach of Serious Gaming, the application of a web-based Geographic Information System (GIS) based tool for both risk communication and maintenance prioritization. Furthermore, this part involves an elaboration of the potential of infrastructure funds.

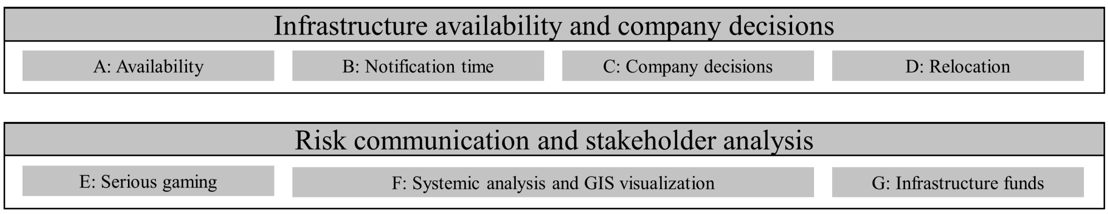

Figure 1.1: Contributions of the present dissertation - structured studies

Since the concept of resilience is examined in this thesis primarily from an industrial engineering perspective, the concept of total cost of ownership (TCO) plays a central role. TCO comprises all costs associated with an investment with the aim of informed investment decisions (Ellram and Siferd, 1998). By considering all potential costs and threats when prioritizing maintenance measures, insights for researchers and practitioners are derived, which can contribute to improving the resilience of transport infrastructure.

The remainder of this dissertation is structured as follows: Chapter 2 includes an overview of relevant terms, literature, and research gaps. Following, chapter 3 highlights the selected methodology. The results of the individual studies are emphasized in chapter 4. The managerial implications of the studies are discussed in chapter 5. Finally, the dissertation is summarized and critically examined in chapter 6. The companion articles are attached at the end of the dissertation.

2 Theoretical Foundation

To contribute to the body of literature on infrastructure maintenance and its interdependencies with company decisions, first, an outline of relevant definitions within the scope of risk and resilience in the context of Supply Chains (SCs) and IW transportation (IWT) is given. The second subsection then provides insights into the maintenance of IWs and the requirement for the application of the concept of total cost of ownership and sheds light on the involved stakeholders as well as recent problems. The outline of the foundations of risk perception and communication follows as the present dissertation aims to address and understand the processes and communication of all stakeholders.

2.1 Risk and resilience of Inland Waterways

The following subsection delimits IWT as part of Critical Infrastructures (CIs). It defines risk, resilience, and relative terms before an elaboration on their contextualization follows. The latter comprises the integration of the defined terms within the fields of SCs (section 2.1.3) and IWT (section 2.1.4).

2.1.1 Inland waterway transport as Critical Infrastructure

CIs are "organizations and institutions of special importance for the country and its people where failure or functional impairment would lead to severe supply bottlenecks, significant disturbance of public order or other dramatic consequences" (Federal Ministry of the Interior and Community, 2009). Thus, the potential of both direct and indirect losses makes an infrastructure critical. The infrastructures rated critical vary throughout different countries and in literature: While a vast consensus prevails about most CIs, one encounters different variants in detail. The unanimous definition of CIs includes the sectors of energy, transportation, telecommunications, water, and government/emergency services (Ouyang, 2014).

The definition includes IWs, among others, as part of the transportation sector, although failures in their services go beyond pure transportation disruptions in many respects. This becomes obvious by examining their originate functions: IWs fulfill services such as flood protection, power generation, recreation, water supply, and habitats for fish and wildlife (Oztanriseven and Nachtmann, 2020). Nevertheless, they foremost serve as a transportation mode for passenger and freight transport. While navigable rivers shape the base of IWs, their spatial distribution, flow direction, and lack of natural interconnection make them only partially suitable as a transportation network. To overcome this, artificial connections in the form of channels are built (Radmilovic and Maras, 2011).

Considering freight transport, IWT offers an efficient and high-performance alternative to truck transport and can contribute decisively to increasing transport capacities and unburdening roads at the same time (Federal Ministry for Digital and Transport, 2019). However, the transport mode road often dominates the modal split of freight transport while it exhibits a low share of IWT, while the specific shares vary among countries (Solomon et al., 2021). Meanwhile, representative emission factors demonstrate the need and potential for the preservation and expansion of IWT for sustainable development of the transportation sector (European Commission, 2019; Federal Ministry for Digital and Transport, 2019), as Figure 2.1 shows. Thus, a reliable and IW infrastructure is an essential prerequisite for a desired modal switch from road to shipping (Federal Ministry for Digital and Transport, 2016; Kotowska et al., 2018; Rohács and Simongáti, 2007).

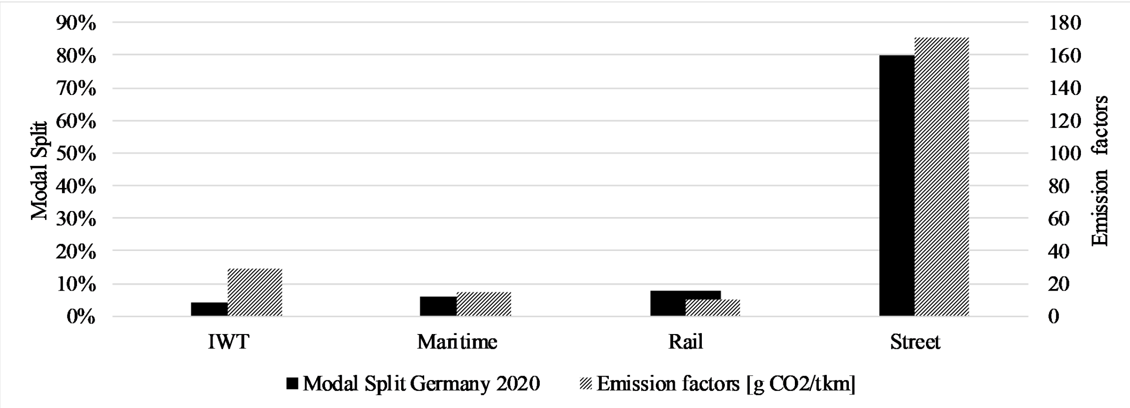

Figure 2.1: Modal split and Emission factors (CO2) of transport modes according to Federal Statistical Office of Germany (2021) and CE Delft (2017)

Nevertheless, infrastructure assets exhibit poor conditions, as Table 2.1 illustrates for different types of buildings necessary to ensure the operation of IWT in Germany. Assets include all facilities required for the waterways' operation, including dams, bridges, canal bridges, culverts, siphons, locks, feed pumping stations, safety gates, weirs, intake, discharge, and outlet structures (Federal Ministry for Digital and Transport, 2014a, 2014b).

River and canal structures	Buildings inspected	Condition insufficient	Replacement or major restoration necessary within 10 years (number)
Locks	314	85%	50
Weirs	240	73%	30
Siphons	352	45%	30
Culverts	69	33%	5
Pumping stations	47	87%	10

Table 2.1: Condition of infrastructure buildings on German Inland Waterways according to Federal Ministry for Digital and Transport (2014a, 2014b)

Steadily deteriorating building conditions arise from a systemic maintenance backlog and a lack of efficiently allocated resources (Federal Ministry for Digital and Transport, 2015; Trechow, 2011; Ministerium für Bauen, Wohnen Stadtentwicklung und Verkehr des Landes Nordrhein-Westfalen, 2016; Frangopol and Liu, 2007; Joeris, 2016). Conclusively, IWs in Germany are in a destitute condition. The overaged infrastructure leads to exponentially growing maintenance requirements and connected costs, while closures cause negative impacts on the users of IWs (German Press Agency (dpa), 2019). Hence, one can assume that significant investments will be necessary for the upcoming years to encounter the overall maintenance backlog and to ensure functional maintenance for the future.

When attempting to reconcile the desired modal shift and the contrary, poor conditions, the principle of *preservation before expansion and new construction* should prevail (Federal Ministry for Digital and Transport, 2016). Thereby, it is necessary to reflect that IWs are part of interconnected infrastructure networks with manifold interdependencies (Rinaldi et al., 2001; Ouyang, 2014; Zhang and Peeta, 2011). They constitute a complex SoS for themselves (Eusgeld et al., 2011; Haimes, 2018) as part of CI, inheriting the need for the prevention of threats since all SoS are subject to multiple adverse initiating events that could originate outside or inside the SoS (Fekete, 2011).

The following subsection elaborates on the terms and definitions of consequences, risks, and the concept of resilience. Then, risk in the context of SCs and the resilience of IWs are emphasized.

2.1.2 Risk, resilience and reliability

According to the previous section, IWs accommodate inherent systemic risks and are also exposed to external risks. The terms risk, resilience, criticality, and vulnerability are strongly interconnected but have no uniform definition since we face interdisciplinary concepts. Nevertheless, established definitions have prominent commonalities in the literature, leading to the following conclusions on reports.

Risk as a measure of the probability and severity of adverse effects (Lowrance and Klerer, 1976; Kaplan and Garrick, 1981) can be more precisely defined as "the probability of harmful consequences, or expected losses (deaths, injuries, property, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between natural or human-induced hazards and vulnerable conditions" (UN/ISDR, 2002). The criticality of a system addresses possible consequences of such hazardous events: criticality as effects of disruption or loss of function for the security of supply of essential goods and services to society (Lenz, 2009; Katina and Keating, 2015) poses the decisive characteristic for the definition of CIs (cf. section 2.1.1).

While the definition of CI focuses solely on the consequences of disruptive events, vulnerability includes the susceptibility of an object or a system to a specific hazard with a particular event severity (Lenz, 2009). Accordingly, vulnerability describes the exposure of infrastructure to disruption, while criticality examines the seriousness of the consequences.

Resilience, as a progressive interdisciplinary term, can be defined as the ability of a system to absorb internal and external risks through adaptive strategies and to recover from negative consequences with appropriate coping strategies (Gaillard, 2010). Accordingly, the robustness (Li and Rong, 2020) and flexibility of a system can be regarded as decisive for its resilience (Jüpner et al., 2018), while the resilience of a system strongly intersects with its availability (Cabinet Office, 2011).

The following holds to delimit availability and reliability as other relevant concepts: Availability refers to the probability of a system operating in normal condition. In contrast, reliability comprises the percentage of time where a system performs its tasks (van Bussel and Zaayer, 2001). Yet, reliability and high reliability theory are of great importance in various disciplines (Shrivastava et al., 2009; Ebeling, 2017; Henley and Kumamoto, 1981).

Figure 2.2 depicts resilience triangles, including reliability parameters such as the Mean Time Between Failure (MTBF) and the Mean Time to Repair (MTTR). This refers to the full functionality of a system connotated with a system performance of "1" while a performance indicator of "0" depicts downtimes as failures; the time to repair in this graph shows linear progressions of recovery, whereas other shapes of resilience triangles are possible, depending on the corresponding resilience capacities (Ayyub, 2003; *Topics Geo Natural Catastrophes 2016*, 2017).

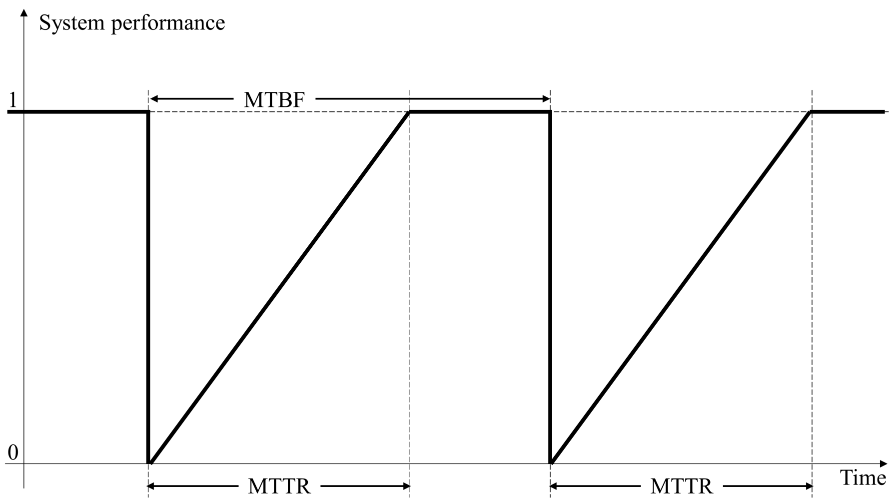

Figure 2.2: Availability parameters and resilience triangle

Meanwhile, possible measures for the resilience of a system are manifold and depend on the discipline and system under consideration. However, the specific quantification of parameters like impact, area, damage, or benefit, e.g., often is vague (Ayyub, 2014; Jüpner et al., 2018). More precise approaches are provided by network-based resilience quantifications, as from Chen and Miller-Hooks (2012). A system's resilience capacities as a supporting concept for evaluation provide a subdivision into absorptive capacity, adaptive capacity, and restorative capacity (Biringer, 2013; Lücker et al., 2019; Ivanov and Dolgui, 2019), as Hosseini and Barker (2016) analyze in the context of IW ports.

Given the interdisciplinary character of the previously stated terms, this dissertation examines the fields of research on these concepts among

(1) Transport infrastructure
(2) Supply Chains, incorporating threats resulting from neglected infrastructure maintenance.

As became apparent, the concepts of reliability, resilience and disruptions are closely linked and are well-studied in literature. Most researchers take the SC-perspective with a predominant focus on the reliability of suppliers rather than the reliability of transport infrastructure (Tomlin, 2006; Linnenluecke, 2017; Dolgui et al., 2018; Cavalcante et al., 2019) The following subsection first illustrates risk and resilience in the context of SCs before heading towards the resilience of IWs.

2.1.3 Risk in the context of Supply Chains

Ellis et al. (2010) contextualize SC risks and stakeholder perception and highlight the role of risk as an individual's perception of total potential loss associated with disrupted SCs. SC risks relate to a possible discrepancy between supply and demand and the resulting consequences. Their source can categorize them: environmental-related, organizational, and network-related risks (Jüttner et al., 2003).

Upcoming trends and challenges for SCs comprise globalization, outsourcing, a change of supplier structures towards system suppliers (small supplier base), a too exclusive focus on efficiency (lean management), and strong reliance on single factories or centralized distribution. These result in an increasing level of observed SC risk (Jüttner et al., 2003; Huth and Romeike, 2016). An efficient SC risk management (SCRM) must manage these rising risks. SCRM must consider differences between direct and indirect impacts of disruptive events on SCs (Baghersad and Zobel, 2015; Haraguchi and Lall, 2015).

Hence, indirect impacts comprise ripple effects leading to non-available transport infrastructure since transportation systems can be identified as part of SCs (Gong et al., 2014). Nevertheless, a wide range of investigations on the resilience and reliability of SCs neglects this important impact category (Linnenluecke, 2017; Dolgui et al., 2018; Taghizadeh and Hafezi, 2012; Kamalahmadi and Parast, 2016; Kochan and Nowicki, 2018).

2.1.4 Resilience of Inland Waterways

Besides the context of SCs, literature provides contributions on risk, resilience and reliability regarding transport infrastructure. Among those are investigations on the vulnerability of transport networks (Mohammadi et al., 2019), on their reliability (Zarghami et al., 2019; Günneç and Salman, 2011), on impacts of disruptive events on infrastructure assets (Stewart et al., 2011) and on the reliability of multi-modal routing (Uddin and Huynh, 2019). Faturechi and Miller-Hooks (2015) moreover provide a review of performance measures of transportation infrastructure systems regarding disruptive events. Nevertheless, the special case of IWs is scarcely regarded: Whereas the resilience of water supply systems is rather present in literature (Altherr et al., 2019; Meng et al., 2018; Shin et al., 2018; Hashimoto et al., 1982), even multimodal approaches hardly consider the resilience of inland navigation (Chen and Miller-Hooks, 2012). Limited applications can be found in Hosseini and Barker (2016) with a focus on ports and Baroud et al. (2014) who consider abstracted stochastic measures to evaluate network resilience.

Thus, the following aims to elaborate on the resilience of IWs considering their complex SoS character with all of its functions: Under normal operation, waterways fulfill diverse functions, which can be ascribed to the respective infrastructure assets. These include water-retaining, water level regulating, traffic-relevant, securing, and crossing (Federal Ministry for Digital and Transport, 2014b; Wehrle et al., 2020). A transfer of the concept of resilience o the application area of IWs must consider potential failures of the individual functions. Thereby, the functions can influence each other within the framework of the complex SoS, leading to the dimensions of economic risk and the potential threat to life and limb, as described in the following.

Figure 2.3 illustrates the economic risk of deteriorating IWs, which addresses its function as transport mode (traffic relevant): An interplay of systemic problems may lead to a decrease in reliability and availability of IWs (cf. section 2.1.1) since deterioration leaves behind reduced transport capacities (Sullivan et al., 2010). Suppose modal shifts cannot compensate for the unavailability of IWs. In that case, manufacturing companies face the risk of production interruptions and thus losses if reliable transports of raw materials and goods are no longer possible (Folga et al., 2009; Helm, 2009). Thus, reduced availability can cause companies to reconsider their choice of location, leaving behind damaged business locations. Consequently, neglected infrastructure maintenance

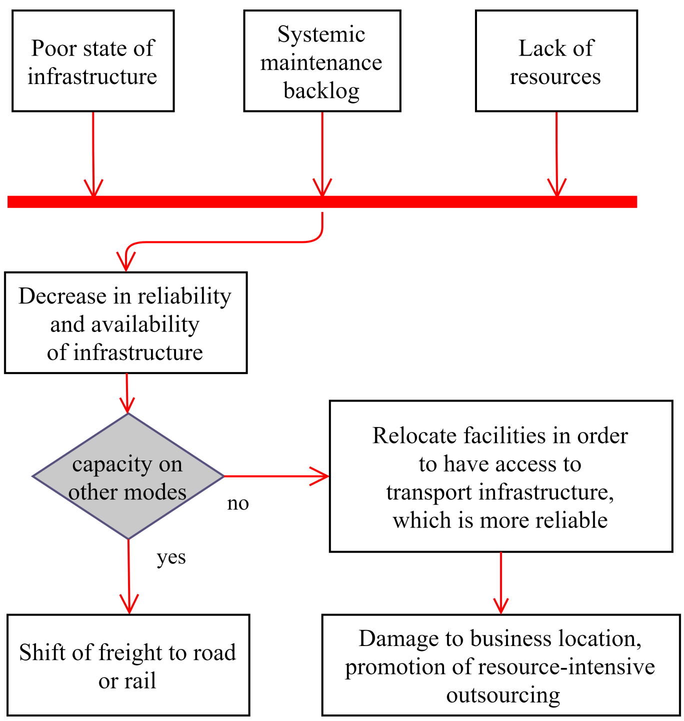

Figure 2.3: Threat and resulting economic risks of deteriorating IW assets

may encourage resource-intensive outsourcing since construction and dismantling sites require a tremendous amount of resources and future transports depending on suppliers and end customers.

In addition to the economic costs, IWs inherit a potential threat to life and limb that can occur in the event of a failure, which may occur in the event of a dam breach, e.g., Jiao et al. (2022); Hüttelmaier et al. (2019). The worst consequences of infrastructure damages comprise damages resulting from flooding events, as provided by Jonkman et al. (2008) and shown in Table 2.2. Further potential threats for the population contain possible dependencies of electricity and water supply on inland navigation. Thus, this severe potential threat must receive special attention when evaluating the criticality of the infrastructure.

	Tangible and priced	**Intangible and unpriced**
Direct damage	• Residences • Capital assets and inventory • Business interruption inside the disaster area • Vehicles • Agricultural land and cattle • Roads, utility and communication infrastructure • Evacuation and rescue operations • Clean up costs	• Fatalities • Injuries • Inconvenience and moral damages • Utilities and communication • Historical and cultural losses • Environmental losses
Indirect damage	• Damage for companies outside the disaster area • A djustments in production and consumption patterns • Temporary housing of evacuees	• Societal disruption • Psychological Traumas • Undermined trust in public authorities

Table 2.2: Different aspects of flood damages
(Jonkman et al., 2008)

2.2 Maintenance of infrastructure systems

Risk analyses of infrastructure systems serve to identify construction elements as potentially critical maintenance objects and to allocate maintenance resources optimally, as well as to provide infrastructure owners and operators knowledge of the possible adverse consequences of neglecting repairing actions (Ellingwood, 2005; Arunraj and Maiti, 2007; Smith, 2011; Holický and Diamantidis, 2014). Thus, the following paragraph elaborates on maintenance management and the associated prioritization of measures before the role of the diverse stakeholders is discussed. This subsection concludes with recent problems in infrastructure maintenance management.

2.2.1 Maintenance management

Considering maintenance management, the term infrastructure asset management becomes relevant. The latter describes coordinated actions to realize value from assets, involving balancing costs, risks, opportunities, and performance benefits (DIN ISO 55000, 2014). The key objective of maintenance management is to maximize the availability and reliability of the assets, which is attained cost-effectively and in accordance with environmental and safety regulations (Kobbacy and Murthy, 2008). Maintenance actions can be corrective, precautionary, or autonomous (Ding and Kamaruddin, 2015; Kobbacy and Murthy, 2008). In the context of transport infrastructure, recent literature employs various objectives. In contrast, those responsible prefer to rely on traditional methods of maintenance planning based on the subjective appraisal of domain experts and past experiences (Morcous and Lounis, 2005; Allah Bukhsh et al., 2019).

The form and interval of inspections vary depending on the object type and with generalized considerations of hazard and safety issues. In contrast, executive authorities conduct principle inspections on fixed time intervals, completed by surveillance and specific ad-hoc inspections. The latter is undertaken after incidences such as impact damage or flooding; the outcome of these inspections is primarily a classification of existing damages (Schmidt-Bäumler, 2020).

To date, infrastructure measures are performed according to fixed time intervals for maintenance, while projected efforts of construction and preservation are often prioritized in an inscrutable manner. Meanwhile, literature provides various maintenance applications based on multi-criteria or multi-objective optimization, where cost is significantly predominating the applied objectives (Syan and Ramsoobag, 2019; Meneses et al., 2013). Maintenance optimization models with multiple objectives mainly provide bi-objective problems by minimizing costs and maximizing structure performance (Allah Bukhsh et al., 2019; Elhadidy et al., 2015).

Referring to the elaborations on resilience (section 2.1.4 and Figure 2.2), resilience-based maintenance strategies should aim to reduce MTTR and increase MTBF. Moreover, it should consider all kinds of risks. Due to deteriorating building conditions, reductions of resilience arising from neglected maintenance measures predominantly endanger the conditions of building structures.

As outlined before, avoiding fatal consequences of infrastructure failure requires implementing maintenance measures where system-critical elements prevail, enabling existing resources to be optimally used. Since causes for failures of IWs are manifold, threats are divided into three classes: human/technical failure, natural phenomenon, and terror/war attacks (Federal Ministry of the Interior and Community, 2009), whereas human/technical failure, includes the predominate risk of neglected maintenance. This gains particular relevance when common cause failures (Kvam and Miller, 2002; Chae and Clark, 1986; Vaurio, 2005) come into focus beyond a single cause of failure since inefficient maintenance planning may accelerate the before-mentioned scenarios. Yet, the complex SoS character of infrastructure maintenance (Chowdhury et al., 2020) can be inherently addressed by complex decision-making as described by Edelenbos and Klijn (2007).

Conversely, maintenance strategies must deploy scarce resources not only in a cost-minimizing manner but under consideration of all types of internal and external costs. Therefore, costs incurred by transformations of business locations (Button et al., 1995; de Bok, 2009; Hossain et al., 2019; McCalla et al., 2001; Coetzee, Petrus J. van V. and Swanepoel, 2017) must be offset to the infrastructure investments (Bardt et al., 2014; Behrendt and Trojahn, 2013), according to the concept of total cost of ownership (Ellram, 1993) which is described in the following.

2.2.2 The role and concept of total cost of ownership

The concept of TCO originates from the ambition to understand SC-related costs in a corporate environment (Ellram, 1993), aiming to offer firms a method to compare different choices of suppliers (Degraeve and Roodhooft, 1999). The underlying idea of TCO is that those suppliers with the most attractive pricing are not always the most beneficial. Thus, investment decisions must evaluate the item itself and the customer's interface with the supplier (Ellram, 1993; Wouters et al., 2005).

The basic concept of TCO comprises quantifying all costs associated with the purchasing process throughout the entire value chain of the firm (Degraeve and Roodhooft, 1999). Therefore, the buying side determines all the costs related to the acquisition, possession, use and disposition of a good or service (Ellram and Siferd, 1998). Thus, TCO considers all the costs that arise from a transaction, including costs from the first idea onwards to supplier collaboration up to problems that come up after completion. To do so, the concept aims to assign a monetary value or a score to the different options and support a more rational decision-making (Ellram, 1993). Possible categories for cost drivers of TCO are operation costs, quality, logistics, technological advantage, supplier reliability and capacity, maintenance, inventory costs, transaction costs, life cycle, initial price, customer-related costs, opportunity costs, and miscellaneous costs (Ferrin and Plank, 2002).

Being usually used for SC buying decisions in a corporate context, this thesis adopts the concept of TCO for maintenance prioritization of transport infrastructure. Decisions on maintenance decisions thus must observe financial risks (Langhagen-Rohrbach, 2007; Lam, 1999) and diverse negative externalities induced by the bad condition of the transport infrastructure. These externalities comprise impacts through human, economic, or social losses caused by the failure of individual transportation infrastructure assets (Folga et al., 2009). Moreover, the application of TCO must consider that the condition of the infrastructure network plays a vital role in the economic competitiveness of a country or region (Rietveld, 1994; Helm, 2009).

Regarding the negative externalities arising from the neglected maintenance, the deteriorating condition of the transport infrastructure comes into focus. Folga et al. (2009) describe the consequences of disruptions within the IWs infrastructure as follows: "*As the waterway network is less dense and interconnected compared to other modes of transport, the number of alternative routes is limited. On top of that, the nature of the cargo hardly allows the use of alternative ways of transport. Thus, a closure of one critical facility can lead to high costs to the economy*" (Folga et al., 2009). A TCO-aligned concept must incorporate this impact as a cost when considering infrastructure investments. The decision not to invest or invest too little can affect whether transport infrastructure assets fail, which imposes costs on the economy. Moreover, any infrastructure failure can have a cascading impact on other infrastructures as infrastructure networks are complex and interconnected, which may contribute to the amplification of asset failures (Little, 2002; Laugé et al., 2015; Chen and v. Milanovic, 2017; Rinaldi et al., 2001; Kelly, 2015; Ouyang, 2014).

Thus, considerable negative externalities involve consequences of insufficient safety measures, harm to a country's economy (Helm, 2009), and potentially high additional costs for the user due to the resulting congestion or detours (Frangopol and Liu, 2007). In contrast, investments in transport infrastructure can improve the productivity of the transport-using sector and the attractiveness of a region (Rietveld, 1994). Accordingly, one must oppose costs of construction and maintenance to costs of potential risks. The latter comprise not only reconstruction efforts but also logistics costs and costs of civil protection, which must also cover the threat to life and limb and the consequences depicted in Table 2.2. To sum it up, paying attention to this provides the potential for an effective resilience-based maintenance strategy.

2.2.3 Stakeholders

Physical assets have many stakeholders that act as groups or individuals and exhibit different requirements, needs, interests, and perceptions of risks. Those responsible for asset management should communicate objectives to all relevant stakeholders (DIN ISO 55000, 2014). Stakeholder analysis thus is conducted via identifying, differentiating, and categorizing stakeholders, followed by investigating relationships between stakeholders with the help of participatory and non-participatory methods (Reed et al., 2009).

In the double role of infrastructure owner and operator, the government is addressed by identifying stakeholders of IWs. At the same time, user-financing achieves an average cost recovery ratio of 25% (10%) in Europe (Germany) (Frerich and Müller, 2004; Stuchtey, 2010). Thus, further stakeholders comprise users as major manufacturing industries, depending CI (Rinaldi et al., 2001; Zio, 2016; Federal Ministry of the Interior and Community, 2009) and the riparian population (cf. Figure 2.4). The following paragraphs elaborate on stakeholders of European waterways, which is transferrable to other countries.

The public sector has sovereignty over policies and legislation on the planning and construction of infrastructure assets and is responsible for taxes and fees to provide modes of transportation. Low risk and costs of failures and the preservation of the reputation of their organization (Tonn et al., 2021), which corresponds to the conservation of electoral votes, are the primary interests of the government as an actor. In addition to the government as a major investor, executive authorities as infrastructure operators direct the actual accomplishment of measures.

The industry as stakeholder comprises foremost manufacturing companies who heavily rely on internal processes of risk management. At the same time, the industry is extensively dependent on exogenous factors such as the accessibility and availability of infrastructure, since SCs often are vulnerable to exogenous shocks (Wagner and Neshat, 2010). Thus, organizations prepare themselves to face disrupted, deterred, damaged, and devolved SCs in the future (World Economic

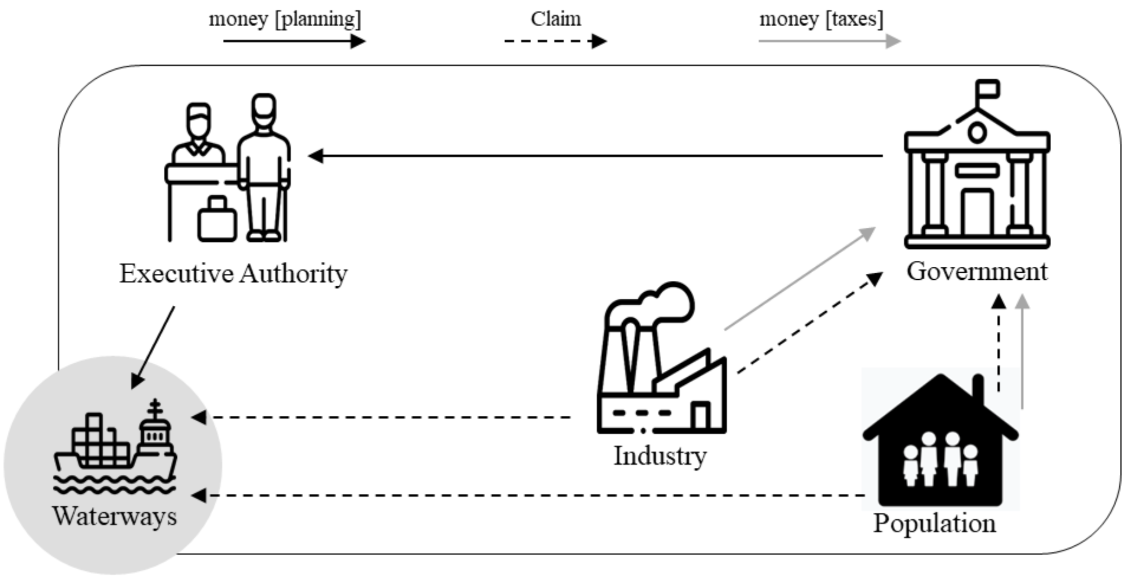

Figure 2.4: Stakeholder of infrastructure maintenance

Forum, 2017), whereas business interruptions can have a variety of reasons (Rose, 2004). However, resilient SCs are required, characterized by agility, visibility, flexibility, collaboration, and information sharing (Hosseini et al., 2019; Christopher and Peck, 2004).

The governmental financing of IWs implies that the indirect donor is the population as the taxpayer. However, direct ways of funding are also possible if the population sees an immediate value in improving infrastructure conditions and - at the same time - reducing risks due to flooding and supply shortages stemming from local infrastructure disruption. Moreover, interdependencies of population and IWs include employment relationships and the perception of and participation in infrastructural projects (Geekiyanage et al., 2020).

Hence, as illustrated before, the consideration of economic costs must be supplemented by further aspects of infrastructure damages, which in the worst-case comprise damages resulting from flooding events, as provided by Jonkman et al. (2008) and shown previously in Table 2.2.

Yet, responsible infrastructure stakeholders must ensure the avoidance and prevention of risks. Transport infrastructure and SC responsibles must cooperate to ensure sustainable economies (Yamada and Febri, 2015). Therefore, infrastructure owners and operators' internal, external, and overlapping processes are of significant importance when considering infrastructure maintenance strategies. These processes range from planning processes to the interaction between companies and infrastructure operators and extend to various kinds of public participation in infrastructure projects.

2.2.4 Problems in infrastructure maintenance

Bad conditions and systemic problems in infrastructure maintenance range across all modes of transport; thus, the large share of the infrastructure funding in recent years was invested in repairments and replacements of existing infrastructure rather than on expansion (Fichert, 2017; Bardt et al., 2014; Federal Ministry for Digital and Transport, 2021), while the amount of traffic has increased significantly (Bardt et al., 2014). Nevertheless, Houlihan (1994) observed early in the 1990s that the need for investment in the different modes of infrastructure was increasing sharply to meet higher demand and maintain the infrastructure. It appears that this issue has been known for several decades. Still, the state of infrastructure has not improved, raising the question of whether the dominating problem is a lack of investment or an inefficient allocation of funds.

To answer this, the following elaborations outline factors contributing to the poor state of infrastructure. These include increased traffic loads since investments in renovation and replacements were never adapted to the new level of usage (Kopper et al., 2013) which is reflected by high investment gaps as analyzed by researchers and practitioners (Bardt et al., 2014; Kunert and Link, 2013; Federal Ministry for Digital and Transport, 2015; Puls, 2013). The poor allocation of the available resources exacerbates the problem further, while one reason is the division of competencies between federal and state governments (Rothengatter, 2000) which inherits ineffective and inconsistent responsibilities and thus creates a principal-agent problem, resulting in inefficient resource allocations (Fichert, 2017). Additionally, project prioritization is not only determined by an unbiased cost-benefit analysis but is subject to political negotiations. This circumstance may bring projects with a low capacity utilization and high capacity reserves forward while urgent projects with more positive network effects are postponed (Bardt et al., 2014; Kopper et al., 2013).

In addition, infrastructure planning is rarely fully transparent, and the outcomes are, in most cases, not analyzed afterwards (Short and Kopp, 2005). Moreover, the political character of the infrastructure planning process promotes a free-rider problem: the state, who is also the primary beneficiary, makes proposals for infrastructure projects. Meanwhile, the federal government bears the costs of infrastructure projects. In consequence, large projects with a questionable use for federal transport are carried out at a high cost since the interests of a few influential parties threaten to take precedence over the benefits to society as a whole (Bardt et al., 2014).

Furthermore, inter-year planning is complicated due to the recurring political dispute over the annual budget. This leads to the fact that mainly tiny construction lots are tendered and prevent an efficient construction process resulting in long construction times (Bardt et al., 2014).

Even if infrastructure decisions are made solely based on a cost-benefit analysis, wrong estimations of the related costs will lead to incorrect assumptions of the cost-benefit ratio of a project. This, in turn, will strongly influence the prioritization of infrastructure projects and, therefore, the efficient and suitable allocation of resources (Flyvbjerg et al., 2003). This circumstance is especially severe as the underestimation of costs is promoted by the system of public tenders, and average cost overruns in the transport sector are analyzed to be 32% (Kostka and Anzinger, 2016) [1]. One reason for underestimating costs is that decision-makers often ignore or underplay risks as a tactic to get projects started (Flyvbjerg et al., 2003). Additionally, further specifications of the public sector promote cost overruns as contractor according to Debande (2002).

Also, the limited availability of personnel contributes to the bad condition of transport infrastructure. In the past, responsible parties reduced the personnel capacity for planning, leading to a bottleneck in replacing and renovating the (waterway) infrastructure (Kies, 2019). Therefore, even though financing for infrastructure projects may be available, they cannot be conducted because the capacity for planning is too low. The prevailing shortage of skilled workers leaves no expectation to resolve this situation soon (Kies, 2019).

Further factors promoting deficient transport infrastructure conditions include a lack of investment attractiveness from the private sector. Characteristics of the financing system (i.e., annuality, competition with other departments) lead to planning delays and uncertainty about future budgets. The prioritization of lighthouse projects causes a lack of attractiveness of maintenance. More deficits arise from the complexity in planning and the approval procedures, which are often multiple and long-winded (Houlihan, 1994; Klockow and Hofer, 1991; Kopper et al., 2013; Moss, 2011).

In conclusion, the beforehand elaborations reveal multiple reasons for the bad condition of the observed transport infrastructure. Firstly, the fact that existing resources are not allocated efficiently due to the occurrence of a principle-agent problem between the states and the federal state. Reasons for misallocated resources are the influence of political power constellations and biases and the lack of thorough cost-benefit analysis in decision-making. Secondly, transport infrastructure wear increases as many facilities were designed and built around 50 years ago. Hence, traffic loads were anticipated to be lower than they turned out to be. At the same time, increasing traffic loads have caused the already old infrastructure foundations to deteriorate even faster. Thirdly, insufficient financial and human resources availability has resulted in an investment gap as the renovation is taking place too slowly.

2.3 Risk communication and perception

Maintenance management processes aim to prioritize and enable maintenance measures, which requires effective collaboration and communication of all stakeholders. Hence, the role of risk perception becomes relevant, which must be considered when reflecting on the interplay of business decisions as a reaction to implemented or neglected maintenance measures.

[1] In more detail, the average cost overruns amounts to 28% in the road sector, 33% in the rail sector and 68% in the waterway sector, according to Kostka and Anzinger (2016)

2.3.1 Risk communication

Risk analyses in physical asset management necessitate surveying, collecting and interpreting the stakeholder's risk perception and tolerance. This should initiate from a discussion with all interested parties at the earliest stages of the risk analysis, which not only aims at defining their perception and tolerance to risk but also an efficient communication and understanding of the analysis results.

Risk communication is an interactive process of exchanging information and opinion among individuals, groups, and institutions. It involves multiple messages about the nature of risk that express concerns, opinions, and reactions to risk messages or legal and institutional arrangements for risk management (Aven and Ylönen, 2018). Risk communication includes all the messages and interactions on risk decisions, such as announcements, warnings, and instructions that experts' sources and non-expert audiences exchange among and between them. It also includes messages not strictly about risk but all relevant factors related to risk management. Risk communication is successful when it raises the level of understanding of relevant issues or actions. Those involved should be satisfied to be adequately informed within the limits of the available knowledge. Several communication formats are available, with a pertaining grouping into three main groups: verbal, numerical, and graphical (Timmermans and Oudhoff, 2011), the last one allowing the visualization of risk-related information. Risk visualization employs charts, conceptual diagrams, visual metaphors, and mapping techniques to improve the understanding and subsequent management of risks in specialist and management teams or stakeholder groups.

Surveys of companies within Germany reveal that companies assess the condition and expansion of the transport infrastructure more poorly in 2016 than in 2010. In contrast, they perceive improved accessibility at the same time (IHK Darmstadt Rhein Main Neckar, 2017). This provides insights into risk perception and its evolution of infrastructure as a location factor, although again, inland navigation plays only a minor role due to the group of participants.

The broader field of risk communication involves the transmission of expert knowledge (Cooke, 1994) which provides the potential of enhancing situational awareness (Endsley, 1995) as one of the challenging areas related to CI protection (Alcaraz and Zeadally, 2015). Current methods of risk communication in combination with stakeholder and risk analyses comprise digitized models which find application in the field of infrastructure SoS with the help of diverse modeling techniques or languages such as unified modeling language (UML) or with the help of GIS. Meanwhile, those applications are primarily used to aid research processes due to the complexity as an inherent property of CI systems (Bagheri and Ghorbani, 2010).

2.3.2 Risk perception

The status of risk as a mental construction also makes the stakeholder's risk perception and risk attitude relevant parts of a risk analysis. Risk perception as a subjective way in which people judge the characteristics and the severity of a risk, it is a cognitive process influenced by experiential, emotional, sociological, anthropological, and many other factors. It affects people's attitudes towards risk and their risk tolerance, with the latter being the amount of risk that an individual is willing to accept in pursuing some goal (Vrijling et al., 2006). Risk tolerance may be mediated by the general tendency to risk aversion of the person and the personal value attached to the goal of a particular situation. Some goals may be judged as more acceptable with respect to higher risk exposure levels than other purposes. Meanwhile, an acceptable risk level is strongly determined by the perceived level of current risk (Slovic et al., 1980).

Technologies offer not only social benefits to society but also impose social costs on it. Hence, the ratio of costs and risks forms an elementary basis for the social acceptance of a technology, whereby society's scope for action distinguishes between voluntary and involuntary activities (Starr, 1969). Starr (1969) observes objective measures to assess the interplay of risk and benefit, neglecting the inherently subjective character of risk perception. Considering expert risk assessments, the concept of risk perception also implies that these assessments are susceptible to biases (Slovic et al., 1980). Characteristics that determine risk perception comprise voluntariness, the immediacy of effect, knowledge about risk, control over risk, newness, chronic-catastrophic, common-dread, severity of consequences (Slovic et al., 1980), and trust (Siegrist and Cvetkovich, 2000). Thereby, Siegrist and Cvetkovich (2000) observe that trust and risk perception correlate when respondents rate their knowledge of the survey item as low.

Risk perception of transport infrastructure reveals a connection with its availability and thus reliability since these refer to the time-spans, where stakeholders are confident with the systems' performance. Once a stakeholder perceives these times to be too short, they feel called upon to act and feel threatened if they do not have or see any supportive choices for action. Thus, risk perception is also dependent on the risk horizon, which is longer for infrastructure than for the planning of facilities (Muir-Wood, 2015).

3 Research Objectives

The previous chapter demonstrated the scope of recent research and practical implications of infrastructure maintenance planning. Nevertheless, multiple research areas for enhancing IW resilience have not been studied thoroughly yet. Therefore, the dissertation's primary motivation is to provide approaches to optimize maintenance activities. The following chapter gives an overview of the pursued research objectives. Meanwhile, the dissertation is designated to contribute to the body of literature and improve the outcome and usage of future opportunities to enhance infrastructure resilience with the help of seven scientific studies.

Hence, the provided studies aim to shed light on the interdependencies of infrastructure availability and company decisions, as well as on the potential of stakeholder analysis and risk communication, as outlined in the following conceptualized research objectives (sections 3.1 and 3.2). Thereby, the concept of TCO frames the studies. This request requires a stronger focus on the externalities of infrastructure management, which are examined in detail. Thus, section 3.3 locates the studies within the decision processes of stakeholders before a detailed presentation of the studies' results follows in chapter 4.

3.1 Infrastructure Availability and Company Decisions

The interdependencies of available infrastructure and company decisions must be identified to address CI elements within the scope of a resilience-based maintenance strategy. Only this will enable predictions on how companies react to the allocation of measures and thus on the effects that can be expected on entire business locations when scarce resources have limited deployment options. Literature provides a broad range of methods to model CI systems (cf. review by Ouyang, 2014). Corresponding risk, vulnerability, and resilience individually or with overlaps subject of research investigations (Giannopoulos et al., 2013; Utne et al., 2011; Faturechi and Miller-Hooks, 2015; Fekete, 2011; Federal Ministry of the Interior and Community, 2009; Ukkusuri and Yushimito, 2009; Novotný et al., 2015; Theoharidou et al., 2010, 2009; Katina and Hester, 2013; Scott et al., 2006; Taylor and D'este, 2003; Lenz, 2009; Ezell, 2007; Shin et al., 2018; Shadabfar et al., 2022). Nevertheless, the interconnection of company decisions and infrastructure maintenance is scarcely analyzed in the literature.

Even though literature provides investigations on the economic effects of transport infrastructure, focusing on accessibility (de Bok, 2009) but neglects the concept of TCO: It is recognized that SC disruptions expose firms to operational and financial risks (Craighead et al., 2007), but the effect of deteriorating business locations due to neglected infrastructure on total maintenance costs is hardly examined. Thus, the following sub-objectives are formulated and outlined in the subsequent sections:

(1) to analyze historical data of infrastructure failure to conclude the economic criticality of neglected maintenance measures (sections 3.1.1 and 3.1.2),
(2) to observe location preferences of manufacturing industries to derive implications on the development of business locations regarding their access to transport infrastructure (section 3.1.3),
(3) and, based on the previous insights, to examine critical threshold of infrastructure availability promoting relocation activities of firms (section 3.1.4).

3.1.1 Measure the reliability of transport infrastructure networks as part of supply chains

As outlined in section 2.1.4, there is only limited evidence in assessing the reliability of IWs. Investigations on other transport networks mainly focus on link failures (Günneç and Salman, 2011), while IWs and their buildings seem to require special considerations to analyze node failures by approaching IWs as networks connected by its buildings such as locks.

However, from the perspective of the industries, evaluating the reliability of transport infrastructure is indispensable to enabling an effective SCRM. In contrast, common literature on SC network reliability centers on supplier reliability over the associated transport network (cf. 2.1.3). Overall, there is already a lack of literature on calculating SC reliability measures under the combined consideration of 1. various kinds of infrastructure failure and maintenance measures (cf. section 2.2.1), 2. their historical documented data, and, 3. restorative capacities of infrastructure assets (cf. section 2.1.2).

This gap can be addressed by reliability theory as well as by field studies based on empirical data (cf. section 2.1.2), which is why study A aims to transfer basic models from reliability theory toward the assessment of transport networks from an SC perspective.

3.1.2 Identify critical warning times for predictable CI closures

Since executive authorities publish notifications about upcoming IW closures (WSV, 2022) riparian manufacturing companies can react within their logistics planning, depending on the length of the warning time. This interrelationship is essential to business operations since too short warning times can fall short to prevent production stops. Hence companies and SCs are highly dependent on planning security (cf. section 2.1.3), requiring adequate warning times in advance of infrastructure closures to avoid limiting available mitigation strategies.

Thus, available data about historical disruptions can be employed to link CI protection, expert knowledge, and SCRM. The latter should enable the incorporation of exogenous factors such as infrastructure availability. Nevertheless, literature does not investigate the role of warning times in SCRM regarding infrastructure closures. Thus, this research gap is addressed in study B.

3.1.3 Understand company decisions as reaction toward neglected maintenance of public transport infrastructure

Regarding company decisions and their interconnections to the availability of transport infrastructure, manifold insights can be found in literature concerning the following topics: impacts of disruptions (Ke and Verma, 2021; Käki et al., 2015; Laugé et al., 2015; Shukla et al., 2011), under the influence of congestion and queueing (Manfredi et al., 2018; An et al., 2015), identification of recovery profiles (Ayyub, 2014; Jüpner et al., 2018), industrial vulnerability (Little, 2002; Blackhurst et al., 2018; Wagner and Neshat, 2010), measurements and costs of preventing disruptions (Scholten and Rothstein, 2012; Lim et al., 2013; Sawik, 2019; Tomlin, 2006), quantification of the damage caused by disrupted SC's (Baghersad and Zobel, 2015; Crowther, 2008), and identification of cascading events (Buldyrev et al., 2010; Rinaldi et al., 2001).

Early approaches to analyze the impact of disruptive events on good movements concern earthquakes and subsequent rerouting and damages to the economy (Hansen and Sutter, 1990; Willson and United States. Bureau of Transportation Statistics, 1998). Recent literature also deals with lessons learned from disruptive events regarding SC's (Haraguchi and Lall, 2015; Matsuo, 2015; Fujimoto, 2011; Park et al., 2013; Chee Wai and Wongsurawat, 2012). Santos and Haimes (2004) analyze inoperability due to terrorism regarding interconnected infrastructures.

Nevertheless, the literature does not investigate the local affectedness of business locations by maintenance backlogs of infrastructure assets considering company decisions. Thereby, both the SoS character of IWs and the risk perception of stakeholders influence the respective decisions. Yet, understanding the reactive measures of manufacturing companies on infrastructure failures is fundamental when developing resilience-based maintenance strategies for infrastructure assets. study C addresses this research gap.

3.1.4 Analyze incentives for facility relocations in dependence on infrastructure availability

As promoted before, global SCs are highly dependent on the availability of transport infrastructure, which in turn forms a prerequisite for functioning business locations. As demonstrated in the previous section, the impact of unavailable infrastructure on transport logistics is a scarcely studied field in literature. Furthermore, Figure 2.3 depicted earlier that the timely reference of risk-avoiding measures from industries is essential in assessing the impact of unreliable infrastructure on business operations. Thus, in case of disrupted IWT and simultaneously non-availability of capacities on other transport modes for modal shift options, relocation of facilities becomes an attractive option for manufacturing sites. This scenario addresses the planning levels of SCM (Melo et al., 2009) since literature recognizes that infrastructure condition clearly determines operating costs (Chatti and Zaabar, 2012), whereas the understanding of the integration of infrastructure conditions in strategic business decisions is still a rarely considered field of literature (Lambiase et al., 2013; Gast et al., 2020).

These illustrated developments endanger business continuity (Christopher, 2016) and whole business locations, thus posing a threat to the welfare of societies. This, in turn, must be well-considered when encountering maintenance backlogs and deteriorating infrastructure conditions. Nevertheless, the interconnection of relocation as a strategic reaction to unavailable infrastructure promotes a gap in the literature: While facility location planning (FLP) is a well-studied and broad field of research (Melo et al., 2009; Farahani et al., 2009), the relocation of existing facilities is addressed rather scarcely by dynamic location problems (Boloori Arabani and Farahani, 2012) where the focus is instead on demand-side incentives (Wesolowsky and Truscott, 1975; Farahani et al., 2009), neglecting other exogenous influences. Infrastructure is commonly identified as the most essential factor of business locations (Rezaei et al., 2018).

As one of the few who incorporate infrastructure within their considerations, de Bok (2009) analyze the influence of infrastructure accessibility, among other factors, on the probability of relocating facilities but neglect the availability of infrastructure. Thus, study D addresses this research gap of investigations by considering infrastructure availability as an influencing factor in relocation decisions of manufacturing companies.

3.2 Stakeholder Analysis and risk communication

To address CI elements within the scope of a resilience-based maintenance strategy, internal and external processes and the risk perception of those responsible must be observed. Only this will enable improvements in risk communication, allowing for determining the optimal deployment of scarce resources. To effectively address this research need, the following sub-objectives are formulated and outlined in the subsequent sections:

(1) to analyze and understand processes across stakeholders of IW maintenance (section 3.2.1),
(2) to develop a systemic approach of risk assessment and visualization as a software-based decision support tool (section 3.2.2),
(3) and to examine the potential of innovative infrastructure funds (section 3.2.3).

3.2.1 Understanding processes across stakeholders

Modeling infrastructures requires incorporating expert knowledge to understand the interdependencies between the systems correctly and consider individual and systemic specifics in the observed case. These specifics comprise modality, geographical location, structure and process organization of the stakeholders, and their internal and external organization and communication. Due to the

SoS character of infrastructure systems, risk analyses must be conducted in an interdisciplinary way and incorporate the knowledge of all stakeholders (cf. section 2.2.3). To encounter various degrees of uncertainty by rational decisions by decision-makers, risk analysts must make intensive use of expert knowledge (Cooke and Goossens, 2004). Therefore, methods to elicit expert knowledge range from expert interviews to quantitative methods, as (Cooke and Goossens, 2004) demonstrated.

Moreover, using techniques to exploit stakeholder knowledge can simultaneously enhance situation awareness (SA) (Endsley, 1995) among all parties involved. Both require an in-depth understanding of intricate processes and interdependencies, which influence the potential for resilient infrastructure maintenance and are essential for CI protection (Department of Homeland Security, 2016).

Nevertheless, literature provides only a few elaborations on the interconnected application of exploiting experts' knowledge, addressing the SoS character of IWs, enhancing situation awareness, and measuring the observed system's resilience. This research gap is addressed by study E.

3.2.2 Systemic approach and visualization

Considering IW's as SoS, a practical risk analysis requires understanding how failures propagate through the subsystems, which implies identifying the critical SoS configuration. Moreover, it requires the choice of a valid model for the simulation of the failure pathway, which contains mathematical formulations of input, output, state variables, control variables, and random variables (Haimes, 2008).

To address infrastructure as SoS in asset management, fundamentals of maintenance management (cf. section 2.2.1) have to be considered, which leads to the following points to be discussed within the attempted research contribution:

(1) How can risk analysis in integrated infrastructure systems be applied under careful consideration of all objectives in terms of the concept of TCO, taking into account cascading effects?
(2) How can risk visualization account for different risk perceptions and serve the need for risk communication?

Therefore, risk communication between the identified stakeholder groups must be both enabled and observed to exhibit their knowledge within the SoS. Particularly, risk visualization poses a suitable communication format for integrated infrastructure systems, as visualizations lower the access threshold to complex SoS. Hence, interactive discussions based on a shared understanding of the system can fulfill the need to acquire expert knowledge. For this purpose, a visualization of the SoS is indispensable to make system interrelationships evident and accessible to all participants, independent of their position in the system.

Conclusions comprise that it is necessary to develop a comprehensive approach for infrastructure maintenance planning that incorporates all the above requirements. This is addressed by study F.

3.2.3 Potential of infrastructure funds

As outlined in section 2.2.4, problems in infrastructure maintenance comprise both the misallocation of resources and a lack of financial resources, whereby the share in the causal structure cannot be exactly identified. Even though the government is obliged to ensure sufficient infrastructure preservation, risk prevention measures should consider alternative and additional financing options for transportation infrastructures. Those should be analyzed in more detail in order to exploit the full potential of possible improvement measures of IW maintenance.

Infrastructure funds provide one such option. They can offer both stable returns for investors (Panayiotou et al., 2016) and improvements in transport infrastructure funding as decoupling from annual budgets and internalizing external costs (Daehre, 2012). A particular element of this is the distinction from Public-Private Partnerships (PPPs): PPPs address the collaboration of the public sector with the industry as the private sector, whereas funds such as those for flood protection address the general citizenry with the aim of budget increase (OECD, 2020). To evaluate the potential of possible funds, one must examine their mechanisms and the willingness to pay (WTP) of investors. While literature provides elaborations and assessments of WTP regarding flood protection (Entorf and Jensen, 2020; Spegel, 2017), the combination of infrastructure funds for IW is not yet under examination. This research gap is addressed by study G.

3.3 Addressed processes among a resilience-based maintenance strategy of inland waterways

The studies deal with different processes, corresponding decisions among the stakeholders, and relevant procedures for maintenance decisions regarding IWs resulting from neglected maintenance. These address the following various stakeholders:

(1) Industry: SCRM
(2) Infrastructure operator: maintenance management
(3) Infrastructure owner: funding
(4) All: Risk communication

Table 3.1 exhibits that study A and B predominately aim to understand influences on SCRM regarding assessments based on empirical data. Both studies reflect the need to observe the impacts of non-availability on industrial risk mitigation. study C and D also account for the consideration of these aspects in SCRM but, moreover, address maintenance management, as their purpose is to examine the impact of non-available infrastructure on company's decisions. To extend the investigations of these detected problems, study D highlights the options of both modal shifts and relocation of facilities.

Study E supplements improvements in maintenance management by its objective to enhance situation awareness and resilience simultaneously. Moreover, the study demonstrates the integrated application of resilience analysis needed for a resilience-based maintenance strategy. The study

	Study	SCRM	Maintenance management	Risk communication	Funding
Infrastructure availability and company decisions	study A	×			
	study B	×			
	study C	×	×		
	study D	×	×		
Risk communication and stakeholder analysis	study E		×	×	
	study F		×	×	
	study G			×	×

Table 3.1: Addressed Decisions Among Risk-based Maintenance of Inland Waterways

leaves room to continuously improve risk communication. study F also addresses these processes by focusing more on an integrated risk assessment of the SoS IW and its visualization regarding both risk communication among stakeholders and implementing a resilience-based maintenance strategy. study G addresses risk communication as it examines the potential of infrastructure funds, whereby the communication of the use of funds and averted risks are essential.

A description of the studies and their results follows in the next chapter. The managerial implications derived from the cross-study topics are discussed in chapter 5.

4 Summary of studies and results

The following sections provide an overview of the respective study context, the contributions, results, and a brief discussion of the studies A-G as the main contributions of this dissertation. A reference to the associated publication precedes each study.

4.1 Study A: Availability Assessment of IW Systems

The following section refers to the content of the article "Application of the Concept of Supply Chain Reliability for an Availability Assessment of Inland Waterway Systems". This article was written in collaboration with Johannes Gast and was published within the proceedings of the 22nd *Cambridge International Manufacturing Symposium* as Gast and Wehrle (2019).

4.1.1 Study Context and contributions

The study's objective is to transfer the concept of reliability theory (cf. section 2.1.2) toward transport networks under consideration of empirical data reflecting historical closures of locks as infrastructure assets. Thus, the contribution provides a foundation for assessing infrastructure availability from the perspective of manufacturing companies to contribute to their SCRM.

The approach examines infrastructure network availability based on MTBF and MTTR (cf. section 2.1.2). With the developed methodology being applied to the West German Canal Network (WGCN), illustrated by its locks in Figure 4.1), the study is grounded on well-established data (WSV, 2022) and IW networks. However, this field of application serves the need of

(1) addressing the rarely combined examination of IWs as part of SCs, and of
(2) manageable complexity when considering node failures.

Thus, the study contributes to the body of literature by demonstrating the benefit and potential of publicly available infrastructure data for their incorporation into manufacturing companies' SCRM. Moreover, the study sheds light on the restorative capacity of infrastructure assets since the time for recovery is significant for the impact of infrastructure closures but is only scarcely deployed in the respective literature. A presentation of the main results and points of discussion of the study follows.

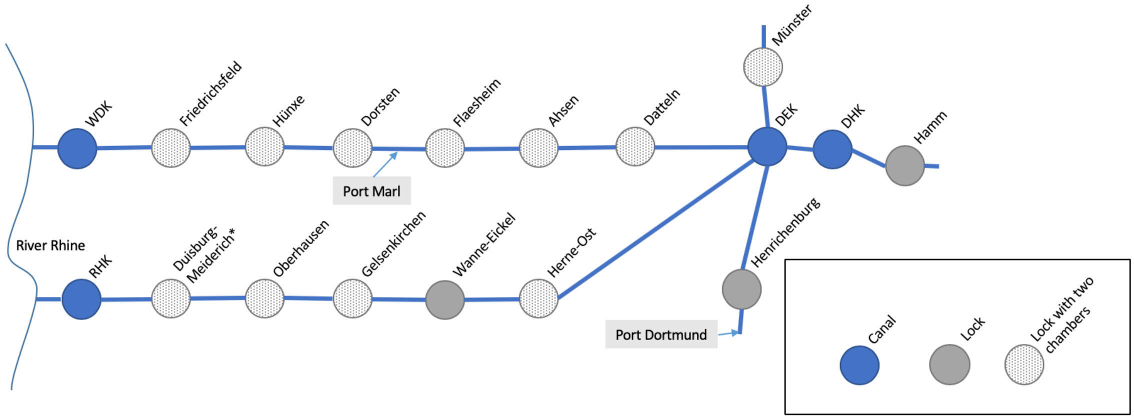

Figure 4.1: Network of the West German canal system
(cf. Figure A.1)

4.1.2 Results and Discussion

Parameters for the reliability assessment were extracted from empirical data and were processed to determine the infrastructure availability of the WGCN. Availability is calculated as percentage of time during which the affected route or building was not subject to a disruption in the history, analogous to the parameters MTBF and MTTR described in section 2.1.2 and as shown by Table 4.1. To quantify the navigability of IW networks, disruptive events under consideration range from maintenance measures to the collapse of a canal bridge over events like rowing regattas and differ in their time of closure and warning times.

The results of study A demonstrate the potential of applying reliability theory to IW networks by considering its component availability. The reliability value as a quantitative indicator for the use in SCRM captures risk likelihoods and simultaneously serves as an indicator for the systems' resilience. As Table 4.1 shows the results of the calculation of reliability parameters for each lock and canal under consideration, the lock of Duisburg-Meiderich [8] reveals the lowest availability among the locks with 94.08%. Further calculations demonstrate an availability of 87.74 % regarding transports from the river Rhine (R) to the port of Dortmund via the lock Henrichenburg [13].

These examinations imply the need to consider infrastructure availability within SCRM processes, namely procurement strategies, and the observation of supplier reliability, inventory costs, and risk mitigation strategies. Hence, investments into risk mitigation can be assessed along with reliability criteria and thus, be prioritized based on their expected effect on the overall infrastructure availability depending on the network configuration and given time scope.

To conclude, study A shows the compatibility of SCRM and reliability theory applied on IW networks. A quantitative indicator using publicly available data could be derived. The developed methodology enables to capture network configuration and time dynamics to be used in both SCRM to prepare risk mitigation strategies (adjusting stock levels, ensuring capacities for modal shifts) and for infrastructure operators to assess the potential of maintenance measures regarding industry operations.

Id	Object	n	MTBF	σ(MTBF)	MTTR	σ(MTTR)	Availability
1	DEK	174	25.54	32.09	2.39	10.36	0.9144
2	DHK	46	97.64	115.87	3.07	10.64	0.9695
3	RHK	182	24.70	28.53	0.78	2.05	0.9694
4	WDK	65	66.55	75.88	0.69	0.83	0.9897
5	Ahsen	46	88.90	198.90	14.08	63.72	0.9813
6	Datteln	51	82.76	218.23	3.24	7.16	0.9986
7	Dorsten	49	85.07	195.93	8.98	41.50	0.9909
8	D.-Meiderich	54	68.20	86.41	14.05	85.92	0.9408
9	Flaesheim	40	101.10	134.44	4.88	13.32	0.9979
10	Friedrichsfeld	96	45.58	63.01	3.64	11.49	0.9945
11	Gelsenkirchen	38	120.59	183.92	5.50	9.85	0.9981
12	Hamm*	21	184.80	245.44	4.62	4.14	0.9756
13	Henrichenburg*	41	107.47	169.98	3.27	8.86	0.9705
14	Herne-Ost	22	172.82	245.13	13.32	44.65	0.9949
15	Hünxe	63	67.37	134.70	5.59	14.73	0,9941
16	Münster	6	711.80	1,025.73	8.06	7.55	0,9999
17	Oberhausen	51	72.44	202.41	20.15	68.90	0,9526
18	Wanne-Eickel*	43	103.50	136,55	2.60	7.68	0,9755

* one-chamber locks

Table 4.1: Calculation of reliability parameters for the West-German Canal Network (cf. Table A.1)

The provided model can be generalized for other transportation networks, while further considerations from reliability theory and SC reliability may extend the assessment by adding environmental parameters, among others. Furthermore, the fit of statistical methods and distributions can be adjusted to provide an improved fit, e.g., by using Weibull functions. Possible seasonal interdependencies and conclusive risk dependencies (Pérez-Rosés, 2018) could extend the study. Potential for further research is also provided by a closer look at single assets, as the capacity of locks and (non-)useful redundancies are not considered yet.

4.2 Study B: Impact of notification time on risk mitigation in IWT

The following section refers to the content of the article "Impact of notification time on risk mitigation in inland waterway transport". This article was written in collaboration with Johannes Gast, Marcus Wiens, and Frank Schultmann and was published within the *Hamburg International Conference of Logistics (HICL)* as Gast et al. (2020).

4.2.1 Study Context and contributions

Study B aims to examine critical thresholds of warning times before IWT closures regarding riparian industries. Therefore, historical data on IW closures is analyzed and extended by experts' knowledge. A mixed methodology approach consisting of a workshop concept on the one hand and data analysis on the other hand form the basis of these investigations.

Within the workshop concept, the responsibles of the research project PREVIEW assembled experts from authorities, science, and industry in two consecutive interactive workshops. One area of interest was identifying appropriate warning times before IW closures (cf. section 3.1.2). Critical thresholds which affect maintenance and logistics operations in IWT should be identified as well as cause-effect relationships of the disruptions' genesis within the network. The first workshop used open discussions and group work to generate insights that are important for the risk assessment of the IW's as SoS and highlighted the interdependencies between SCRM and IWT as mode of transportation. Interactive discussions in the second workshop addressed more targeted issues. These direct interactions were complemented by expert observation in the context of a developed serious game, which was implemented as a collaborative game (cf. study E) and based on previous findings. Thus, the provided research could gain in-depth insights into risk reduction measures. This two-stage concept identified essential connections and processes and served to gain predominantly qualitative data and knowledge.

An extension of the qualitative database uses an analysis of real-world data on historical closures of waterways (WSV, 2022) under consideration of several possible reasons for disruptions. An initial database of approx. 45,000 data records was truncated and analyzed to over 3,000 relevant data records. This account comprises the criteria of local affectedness but also duplicate reports. Notifications published purely for information purposes were not considered here, and further ambiguities in the analysis were identified and taken into account by extracting expert knowledge as part of the workshop concept. Relevant parameters were examined, including the warning time of closures as the time between the publication of the notification of a waterway closure and the actual start of the closure. Thus, quantitative analyses extend the base of qualitative knowledge gained from interdisciplinary research.

To conclude, study B contributes to the body of literature by demonstrating the potential of historical data on infrastructure closures and the combined analysis with targeted extraction of expert interviews. Thereby, the research gap of investigations about warning times in SCRM regarding infrastructure closures is contributed to. A presentation of the main results and points of discussion of the study follows.

4.2.2 Results and Discussion

Study B reveals strong interdependencies of warning times on logistics operations and exhibits a critical threshold of 14 days. The workshops examined the warning times and found through interaction and observation that the industry's options are very limited and strongly depend on the warning time of possible closures. However, with a warning time of at least two weeks as a critical threshold, companies can prevent serious consequences well in advance. This finding means that a shutdown notification should reach the industry two weeks before the start of the shutdown so that logistical processes there can be adapted in the best possible way.

Furthermore, the data analysis shows that this threshold of critical warning times is not undercut on average for full closures. However, the median of the warning times shows that half of all closures examined have less than one day of warning time due to many closures of very short duration. Nevertheless, the study could not prove a correlation between warning time and the duration of the closure to be significant. This observation may be because unexpected incidents with a short warning time also cause long lockout durations. However, maintenance work, which is usually announced for a more extended period of time, can also have a long duration.

Thus, efficient SCRM and logistics planning must address these critical thresholds. Further stakeholders should account for the identified thresholds as executive authorities should consider these within their maintenance planning, e.g., to avoid last-minute closures which endanger normal business operations of riparian industries.

Overall, there is a strong influence of the warning time before a blocking on the business activity of companies. Most closures are below the critical threshold of the warning time, which could conclude that there is no problem. However, the identification of the availability of the WGCN as critical by industry representatives in the past suggests two requirements:

1. SCs must adapt strongly to the availability of the waterway
2. Conversely, to keep this within reasonable limits, infrastructure operators must ensure that longer warning times can be provided. This must be implemented through more efficient maintenance planning to avoid short-term, prolonged closures.

The body of literature is extended by this study regarding the exploitation of available historical data, the extension of literature about IWT, and by linking CI protection, expert knowledge, and SC operations.

4.3 Study C: Economic risk potential of infrastructure failure

The following section refers to the content of the article "Economic risk potential of infrastructure failure considering inland waterways". This article was written in collaboration with Fabian Neff, Marcus Wiens, and Frank Schultmann and has been submitted to a scientific journal (Wehrle, Wiens, Neff, and Schultmann, 2022).

4.3.1 Study Context and contributions

The purpose of study C is to analyze how the private sector is affected by failures of waterways as public transport infrastructure. To investigate the affectedness of riparian industries, two complementary parallel approaches are chosen: A proximity analysis via GIS and a consecutive survey among the identified waterway-dependent industries.

The GIS-based proximity analysis contributes to the literature by enabling the identification of directly affected companies by infrastructure failures by geographical distance. The chosen methodology aims to investigate which businesses rely on different modes of transport. Therefore, the study considers the relationship between location decisions, spatial structure, and modal choice of freight transport. The analysis considers all modes of transportation, whereas a survey taking into focus IWs as a rarely studied field of research extends the results.

Location preferences of business locations classified according to economic sectors are determined based on their current location according to Open Street Map. They are linked with infrastructure access points (APs) of the different transport systems (highway interchanges, rail-road terminals, public ports, and airports). The developed methodology uses Dijkstra's algorithm to calculate the shortest travel times on the road network for given start nodes (industrial sites) and destination nodes (infrastructure APs). APs are own-use company property; the analysis integrates those by radius considerations. Then, the suggested methodology calculates mode-specific average travel times before preference categories are derived by extending and validating the derived travel times using transport volumes from freight statistics. The underlying assumption is that preference categories based on the spatial analyses can only be derived if freight goods statistics and spatial proximities do not reveal notable inconsistencies. Concerning the analysis of IWs, a consequence is that the sectors with a preference for IWT are most affected by interruptions and need special attention in understanding the influence of disruptions on business decisions regarding IWT disruptions.

These concerned industries then are subject to further investigations, namely empirical studies comprising a survey and concluding expert interviews, which target to understand medium or long-term business decisions that may result from infrasructure failure. To understand interdependencies between infrastructure disruptions and business decisions, study C provides key questions and hypotheses, which are addressed by an online questionnaire under consideration of design principles. The key questions are the following:

(1) How do companies perceive a decrease in the availability of IWT?
(2) How does this affect their business activities?

The consecutive expert interviews aim to gain more in-depth knowledge about cause-impact relationships within direct talks using structured interviews with survey participants.

Overall, the empirical studies focus on the following risk-related aspects relevant for riparian industries: Flow of goods and supply relationships, temporal disturbance progressions, vulnerabilities of various sectors, application of risk reduction measures, assessment of the damage caused by interrupted SCs, identification of highly critical event scenarios, the effect of water contamination and shortage of cooling water, and connections with other CI considering power supply and water supply.

To gain combined results, the findings of both approaches are evaluated in a structured manner and aim to investigate and validate coincident interdependencies. Moreover, the results from both methodologies are integrated into a holistic assessment (Wehrle et al., 2020). The case study is investigating the area of North-Rhine Westphalia.

Overall, the study provides a consecutive approach combining GIS analysis and empirical research considering stakeholder knowledge and perception. Furthermore, an exemplary application is demonstrated and validated by stakeholders. Thus, the research gap of investigating the local affectedness of business locations by infrastructure failure is addressed. The study furthermore serves as contribution for the special case of maintenance backlogs of infrastructure assets as cause for infrastructure failure. A presentation of the main results and points of discussion of the study follows.

4.3.2 Results and Discussion

The results of the proximity analysis validated with freight statistics identify location preferences regarding infrastructure access solely for rail freight and freight shipping, but not for highway and air freight. Thereby, the industries of *mining and quarrying, coking plant and mineral oil processing, production of chemical and pharmaceutical products, metal production and processing*, and *energy supply* exhibit high preferences for rail freight transport and freight shipping.

Thus, this analysis identifies industries and, beyond the mere consideration of transport statistics, company locations that will be directly affected by IWT failure based on these location preferences. As scope of action to enhance SC resilience regarding infrastructure failures, affected industries and companies have the alternatives of increasing stock levels, shifting transports, or relocating entire sites if the function of IWT is restricted. The choice of actions depends on the actual threat, the risk perception and feasibility, the economic efficiency of the measures, and the capacities of the alternatives.

The before-mentioned survey of IW-dependent industries and the previous analyses address this scope of action and influencing factors. Thereby, 21 usable responses emerged, which show that more than 60% rely on modal shifts when asked for currently implemented measures to reduce risks arising from waterways. Meanwhile, a much lower percentage of companies point out implementing an expansion of storage capacities and using redundant water supply. Furthermore, those who have implemented modal shift measures in the past are more likely to have planned to do so in the future.

Moreover, the most considerable potential for modal shifts is assigned to short-term shifts to the road, compared to long-term shifts to road and short-/long-term shifts to rail. However, the most significant barrier to modal shifts is perceived as lacking capacities of alternative transport systems for both road and rail, followed by the availability of transport containers, the increased costs of alternative modes, and costs of short-term traffic shifts as Figure 4.2 shows.

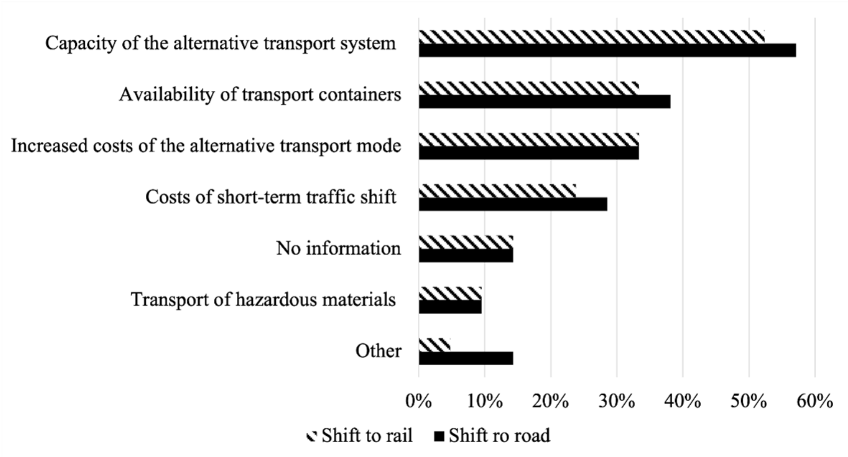

Figure 4.2: Barriers to modal shift
(cf. Figure C.15)

Results also show in consensus with study B that longer warning times significantly relax the companies' abilities: With a warning period of one month, no severe problem is initially feared, whereas a warning period of only one day leads to a much higher impairment of business activity. Figure 4.3 shows the results for an anticipated closure of three weeks. These are hypothetical statements, i.e., estimates based to a certain extent on historical experience. Thereby, the study exhibits a correlation between revenue and the level of constraint as the warning time becomes shorter.

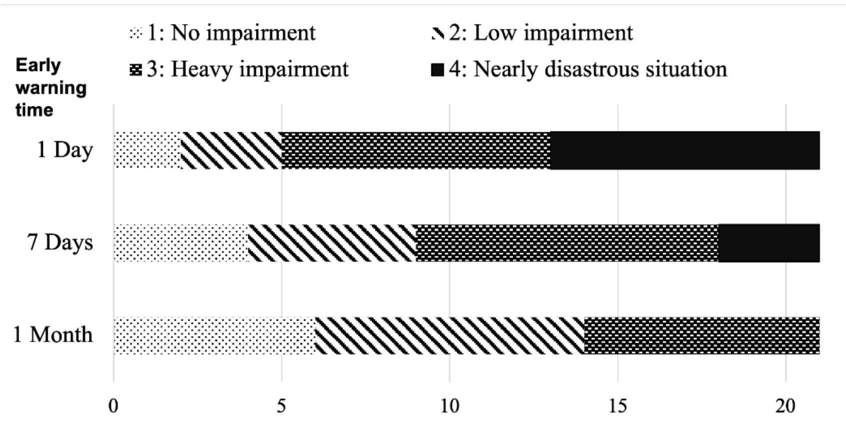

Figure 4.3: Criticality depending on early warning time – closure of three weeks
(cf. Figure C.16)

The combined approach of proximity analysis and empirical studies lead to the following findings: Firstly, early-warning time is of high importance for firms to react to restrictions of IWT. Secondly, infrastructure disruptions hit firms especially hard due to a lack of road and rail capacities. Moreover, the results exhibit that whether the adverse effects of a reduced infrastructure availability can be considerably reduced by sufficient early warning time depends on the company's vulnerability.

Hence, study C provides contributions to a resilience assessment of IWs focusing on economic effects on potentially affected industries. Economic statistics, GIS-Analyses, and industry surveys lead to insights that include essential qualitative and quantitative impacts on industries if waterways are not maintained. A predominance of location preferences for several industrial sectors can be shown while non-existent or not usable capacities of alternative modes of transport pose a threat to business locations if the condition of waterways deteriorates significantly.

Thus, study C supports stakeholders to enable a resilience assessment of their business locations and SCs with the help of the provided survey. Moreover, stakeholders should cooperate to enhance and preserve business locations by sustaining both infrastructure and SC resilience.

Future research could address other external incentives for location-relocation mechanisms and their interaction with the observed factor of infrastructure availability. An integrated development of resilience-based maintenance strategies by exploiting empirical data and expert knowledge should be pursued. Furthermore, an extension of the economic risk potential analysis by an extension of the provided survey towards further companies could contribute to the literature.

4.4 Study D: Modal shifts and relocation of facilities

The following section refers to the content of the article "On the influence of infrastructure availability on companies decisions towards modal shift and relocation of facilities". This article was written in collaboration with Johannes Gast, Marcus Wiens, and Frank Schultmann and has been submitted to a scientific journal (Wehrle, Gast, et al., 2022).

4.4.1 Study Context and contributions

The study's objective is to evaluate companies' business decisions in reaction to availability reductions of IWT, while particular emphasis is placed on cost thresholds of modal shifts which encounter or provoke relocation decisions of whole facilities in the long-term. Figure 4.4 contextualizes the context of decisions which is regarded for in this study.

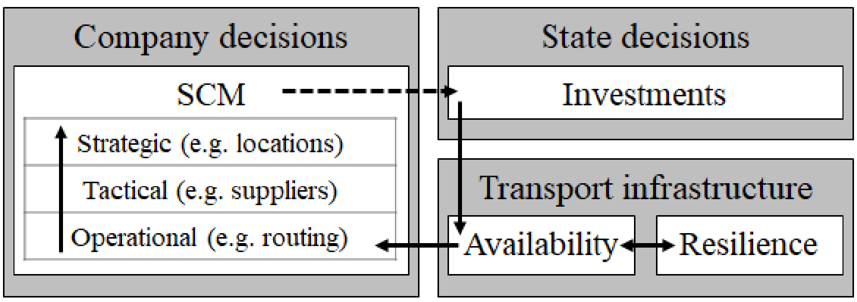

Figure 4.4: Context of decisions
(cf. Figure D.2)

To this end, study D aims to answer the following key questions:

(1) How can cost increase resulting from unavailable infrastructure elements be assessed?
(2) How can the current infrastructure availability be assessed?
(3) What are the costs of infrastructure unavailability?
(4) Which decreases in availability will trigger firm relocations?

To answer these, the developed methodology proceeds as follows. Firstly, a scenario-based transport model enables logistics to assess cost increases due to reduced infrastructure availability. The results of this are then, secondly, integrated into a relocation model, based on de Bok (2009), to assess the probability of relocating facilities by deriving their utility arising from infrastructure conditions.

The transport model uses the Traveling Purchaser Problem (TPP) as a basis (Cheaitou et al., 2021) for vehicle routing and determines the minimal transport costs possible to satisfy total demand. Thereby, total costs and emissions are examined under the assumptions of bi-modal traffic (IWT and truck transport) and full collaboration of carriers to satisfy demands. The model is scenario-capable regarding costs of different route closures and minimizes the total transportation costs, comparing the supply of goods by waterway transport and trucks. Thus, the study answers the first key question stated above as it allows to derive the cost impact of unavailable infrastructure assets under consideration of the extra cost of trucking.

The relocation model then serves to answer the subsequent key questions by calculating the infrastructure availability based on empirical and historical data, whereby the scenario-based character is maintained (Gast and Wehrle, 2019). Risk scenarios incorporate different risk potentials, while escalated costs are calculated, taking into account the cost increase calculated from the transport model in dependency of the scenario-based infrastructure availability and the risk potential. The risk potential refers to the expected duration of infrastructure closure and the vulnerability of the corresponding business locations. Based on these cost calculations, the study enables the calculation of the cost-dependent probability to relocate before a utility-based probability to relocate is provided, based on de Bok (2009). Therefore, the definition of critical availability thresholds succeeds in advance, based on empirical data.

Thus, the final results from the combined models provide an assessment of the current infrastructure condition and sets in relation to the cost and utility function(s). This allows for recommendations regarding infrastructure maintenance since the costs of unavailable infrastructure can be assessed by combining the relocation and transport model via the scenario-specific escalated costs. The developed model also answers the question of decreases in availability that will cause relocations, as the utility-based probability assessment incorporates both preferences of companies and transportation costs from the transport model.

Overall, the study contributes to the body of literature by connecting the concepts of short-term agility of SCRM and long-term resilience with companies' decisions and exogenous factors such as infrastructure availability. A presentation of the main results and points of discussion of the study follows, with the model being applied to a case study of the WGCN, examining the supply of goods of the chemical industry by IWT and trucks across eight examined cases of transport routes.

4.4.2 Results and Discussion

The transport model exhibits cost increases of up to 16.42% among the cases under consideration, as shown in Figure 4.5. This illustration also comprises the escalation of cost increases according to three formulated risk scenarios, whereas the current availability of the observed transport route is depicted. Cost increase and infrastructure availability exhibit moreover linear interrelations within the respective risk potentials. The transport model thereby enhances understanding the impacts of varying demands on modal choices.

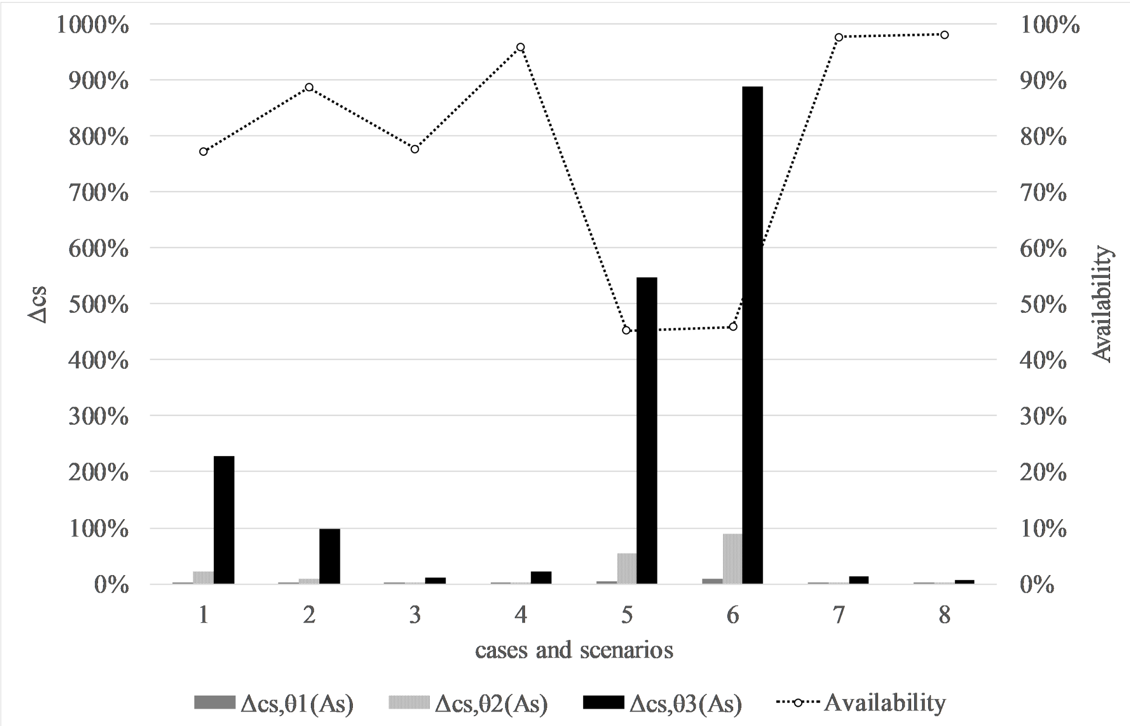

Figure 4.5: Scenario-based cost increase Δc_s and availability A_s at the West German Canal Network (cf. Figure D.5)

The desired probability to relocate is firstly derived in dependency of infrastructure availability (Figure 4.6), while Figure 4.7 approaches the utility-based probability to relocate. Thereby, Figure 4.6 shows similar curves, differing in slope and intersection with the 50% probability of relocation as a proxy turning point, indicating the strong interdependence of infrastructure elements on single routes. More detailed considerations on the Figures and case-specific results can be found in study D.

First, an important finding is that relocations can occur in realistic parameter ranges. To conclude, the results emphasize the importance of scenario-based approaches when examining infrastructure elements regarding their maintenance priority and relevance for business activities. Moreover, the developed methodology allows comparing current availability with critical availability thresholds. Among the findings, a highlight is that highly frequented routes and their possible alternatives

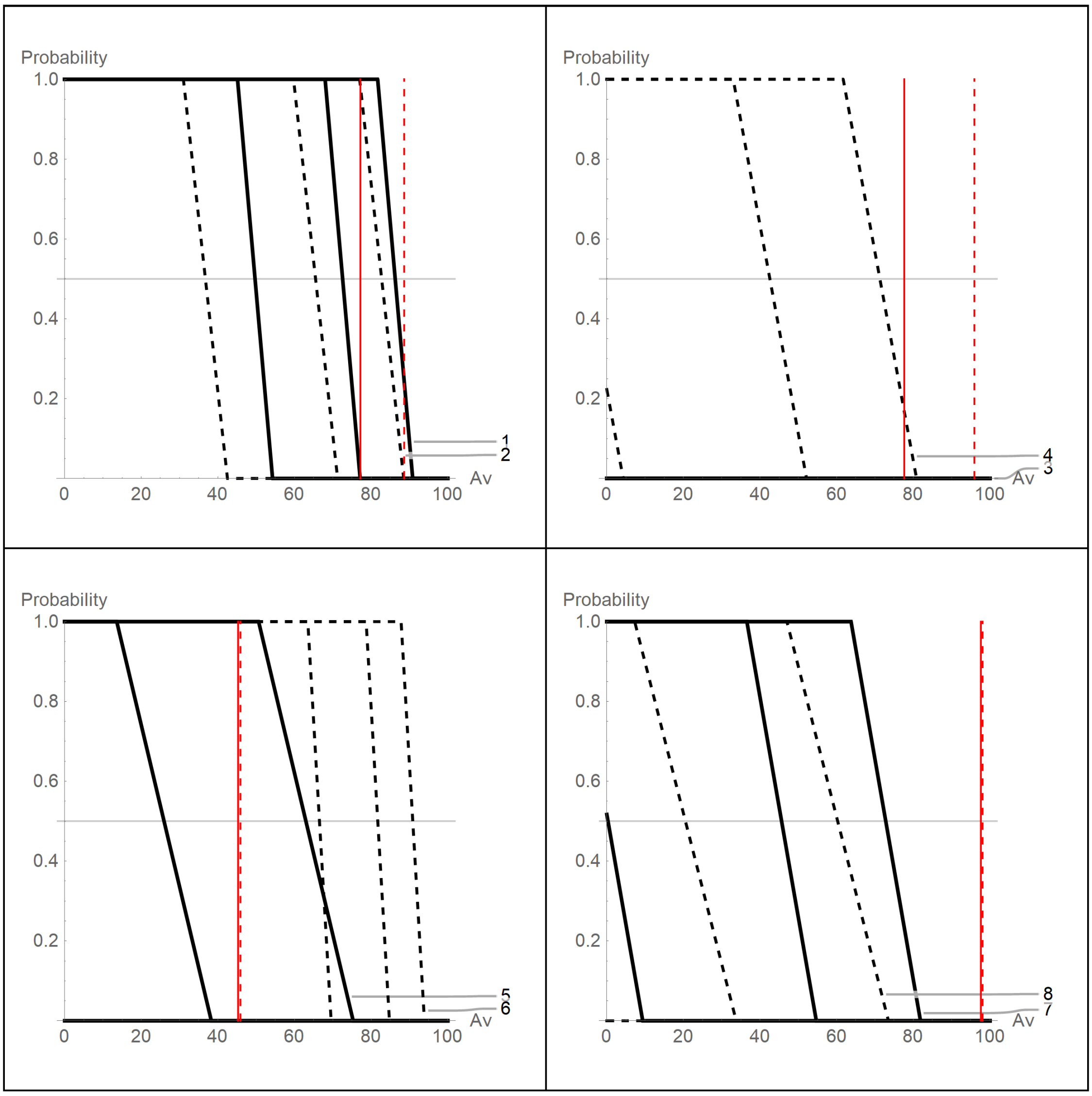

Figure 4.6: Probability to relocate in dependency of infrastructure availability (Av)[1]
(cf. Figure D.8)

require special attention to preserve business locations and avoid relocation of sites being a likely compensation strategy for local companies.

The study accounts for the need for a combined analysis of routing and infrastructure investment decisions, exhibiting the link between infrastructure maintenance and a region's attractiveness as business location. Thus, study D enables decision-makers to identify critical thresholds for infrastructure availability and provides a methodology to analyze business decisions in the context of maintaining public infrastructure. The paper provides insights into the decisive consequences of

[1] Each graph comprises two scenarios (1 line, 2 dashed, etc.) and the three considered levels of relocation costs Δc_R, whereas the most right (black) lines refer to the assumption of $\Delta c_R = 100\%\Delta c_s$. The red lines illustrate the respective current availabilities A_s.

companies' decisions and raises awareness of the relevance of infrastructure investments. Hence, the results can serve to sustain local industries and maintain business locations.

The model can be extended by an extension of considered industries, e.g., coal or arc and stone industry. Moreover, refining the proposed utility functions could contribute to the validity of modeling parameters.

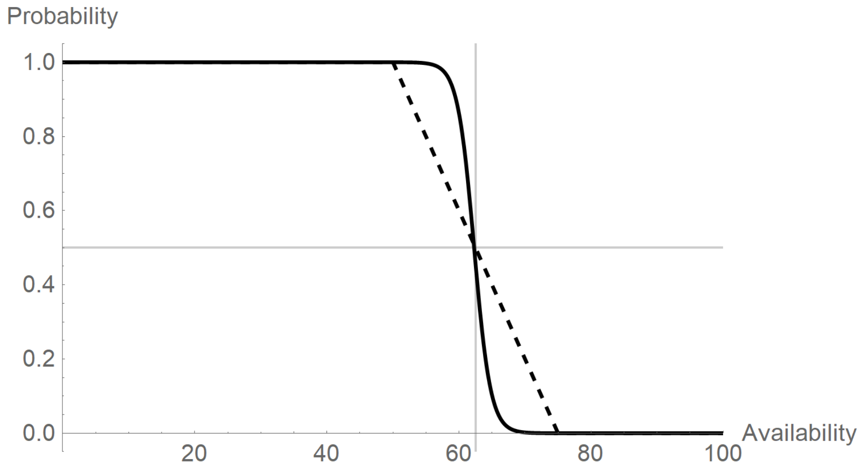

Figure 4.7: Turning points of infrastructure[2]
(cf. Figure D.9)

4.5 Study E: Collaborative serious gaming for the elicitation of expert knowledge and towards creating Situation Awareness

The following section refers to the content of the article "Application of collaborative serious gaming for the elicitation of expert knowledge and towards creating Situation Awareness in the field of infrastructure resilience". This article was written in collaboration with Marcus Wiens and Frank Schultmann and was published in the *International Journal of Disaster Risk Reduction* as Wehrle et al. (2021).

4.5.1 Study Context and contributions

The study's objective is to analyze processes and interdependencies among stakeholders who influence the resilience of IW infrastructure as complex SoS. At the same time, stakeholders themselves should experience and develop an improved situation awareness, reflecting their risk

[2] Determining probability of relocation as function of transport costs and aligned utility function for $\alpha = -50$, $\beta = 0.8$, $\Theta = 2$, $\Delta c_s = 2$, $\Delta c_{R_0} = 100\%$, revealing a turning point at $A = 62.5$, in accordance with case 5.

perception and enhancing the system's overall resilience under consideration. To address this objective, study E provides an iterative framework for eliciting expert knowledge and a subsequent serious gaming application. The latter can be highlighted as a valuable yet emerging research tool that can essentially contribute to the stakeholders' situation awareness and thus improve infrastructure resilience.

Therefore, the study is based on a collaborative board game that emulates real-life decisions of addressed stakeholders of German waterways (cf. section 2.2.3), comprising their roles and interactions. The contribution initially reflects on the developed game enabling a deeper understanding of the real-world SoS, including the impacts of complex decisions. The subsequent use of data extraction from the observed gameplay and other direct techniques of experts knowledge extraction into a Bayesian Network as a resilience assessment tool, as Hosseini and Barker (2016) suggest, extends the analysis.

Figure 4.8 illustrates the use of serious gaming for enhancing situation awareness and contributing to the literature as a research tool. Moreover, the procedure of the iterative design process is shown. One game session comprises an introduction to the game and the gameplay itself, followed by a post-game survey and an analysis of the game, concerning an open discussion about the gameplay and parallels with the real-world SoS.

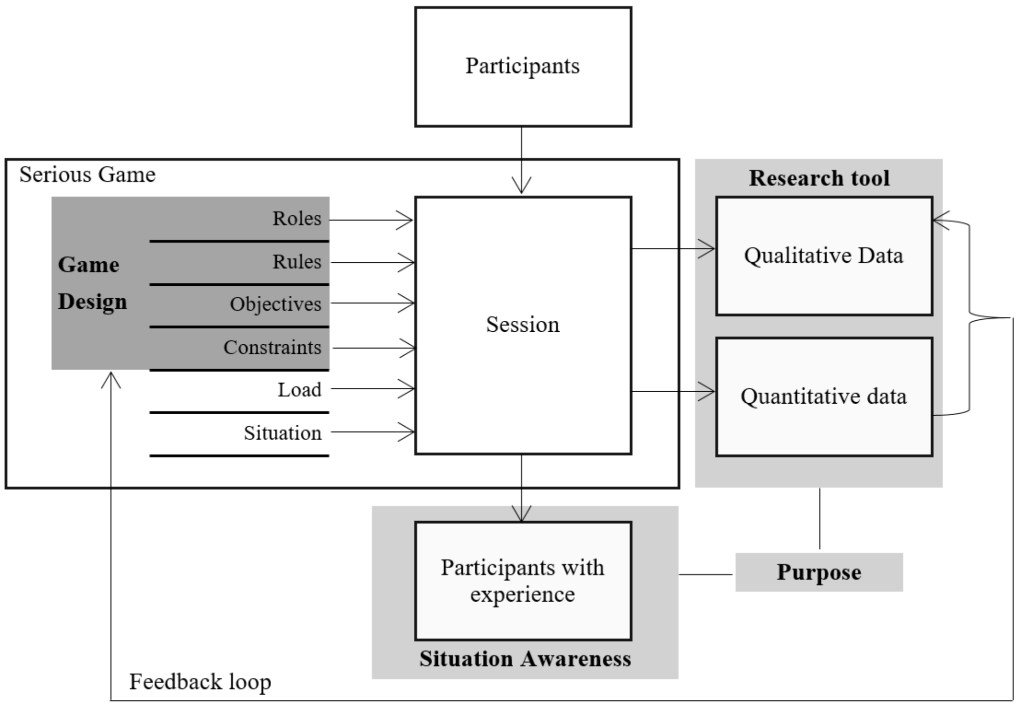

Figure 4.8: Inputs and outputs of serious gaming
(cf. Figure E.3)

The gameplay is oriented to anticipated real-world processes, as depicted by Figure 4.9. At the same time, the specifically developed game is an application for the WGCN with the game board depicting the WGCN and its locks and selected ports which are interconnected via waterways, whereas partially road and rail transport is enabled.

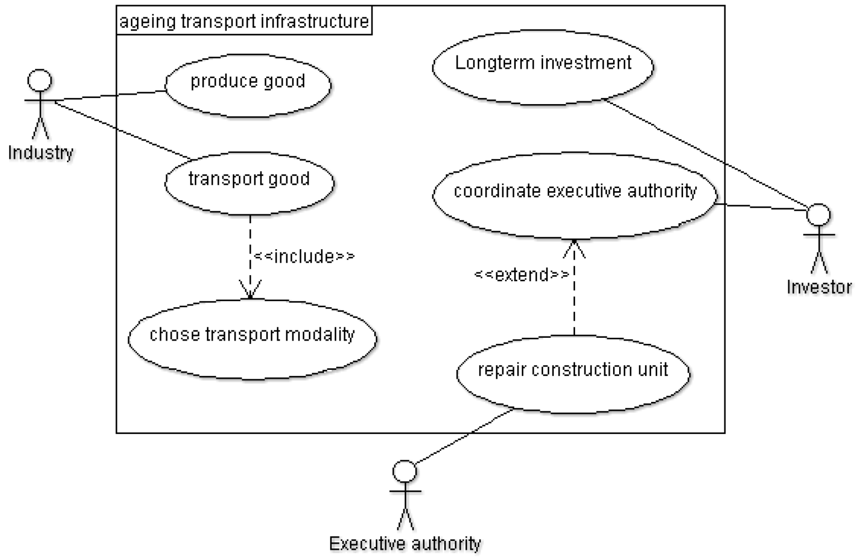

Figure 4.9: Use-case diagram
(cf. Figure E.7)

Overall, the study contributes to the body of literature by extending the analytical and formal account of infrastructure operations management with a serious game and an integrated proposal for use within the scope of resilience assessment using Bayesian Networks. A case study comprising three gameplay rounds with players from differing backgrounds highlights the benefit of enhancing situation awareness and exploiting experts' knowledge. A presentation of the main results and points of discussion of the study follows.

4.5.2 Results and Discussion

The proposed methodology contributes to both the game's purposes as a research tool and its purpose to enhance situation awareness. The results of the application of the collaborative game purpose as a research tool are addressed by research questions, leading to the following exemplary insights:

(1) many aspects could be depicted realistically by the game, such as the scope of actions of the implemented roles or a staff deficit in maintenance
(2) communication and collaboration between investor and executive authority are of utmost importance
(3) timing bias in real-world decisions due to decision-making processes between stakeholders play a significant role in infrastructure resilience

The benefit as a research tool contributes to applying Bayesian Networks as a resilience assessment method for CI as SoS. An initially implemented version of the Bayesian Network based on the three resilience capacities as proposed by Hosseini and Barker (2016) is illustrated within the study and relies on the categories reliability, mode flexibility, redundancies, and building and budget restoration.

Insights gained in the study's scope lead to validation and changes in terms of more effective inclusion of available data and an incentive for a more in-depth quantitative, data-driven analysis. The analysis addresses the variable warning time, among others, and is adjusted to incorporate potential time biases to reflect the extracted experts' knowledge. Furthermore, the personnel capacities as a severe bottleneck of infrastructure resilience are accounted for by adjusting the probability of availability of sufficient human-based resources, taking into account the high number of arising necessary construction measures.

Figure 4.10 illustrates the resulting updated Bayesian Network, which shows a 9.01% reduced resilience compared to the initial Bayesian Network, which is smaller due to the extension of factors among the application of serious gaming. Thereby, the results of the resilience assessment imply the significance of neglected and over- or underestimated influencing factors, whereas the need for even more data-driven assessments is revealed, underlining the potential of additional feedback loops within the research framework. While the resulting resilience values of the network versions provide no meaningful comparisons, their sensitivity with respect to specific parameters are of greater importance. Thus, more precise strategies are enabled by the adjusted network since the adjustment levers are more obvious than before.

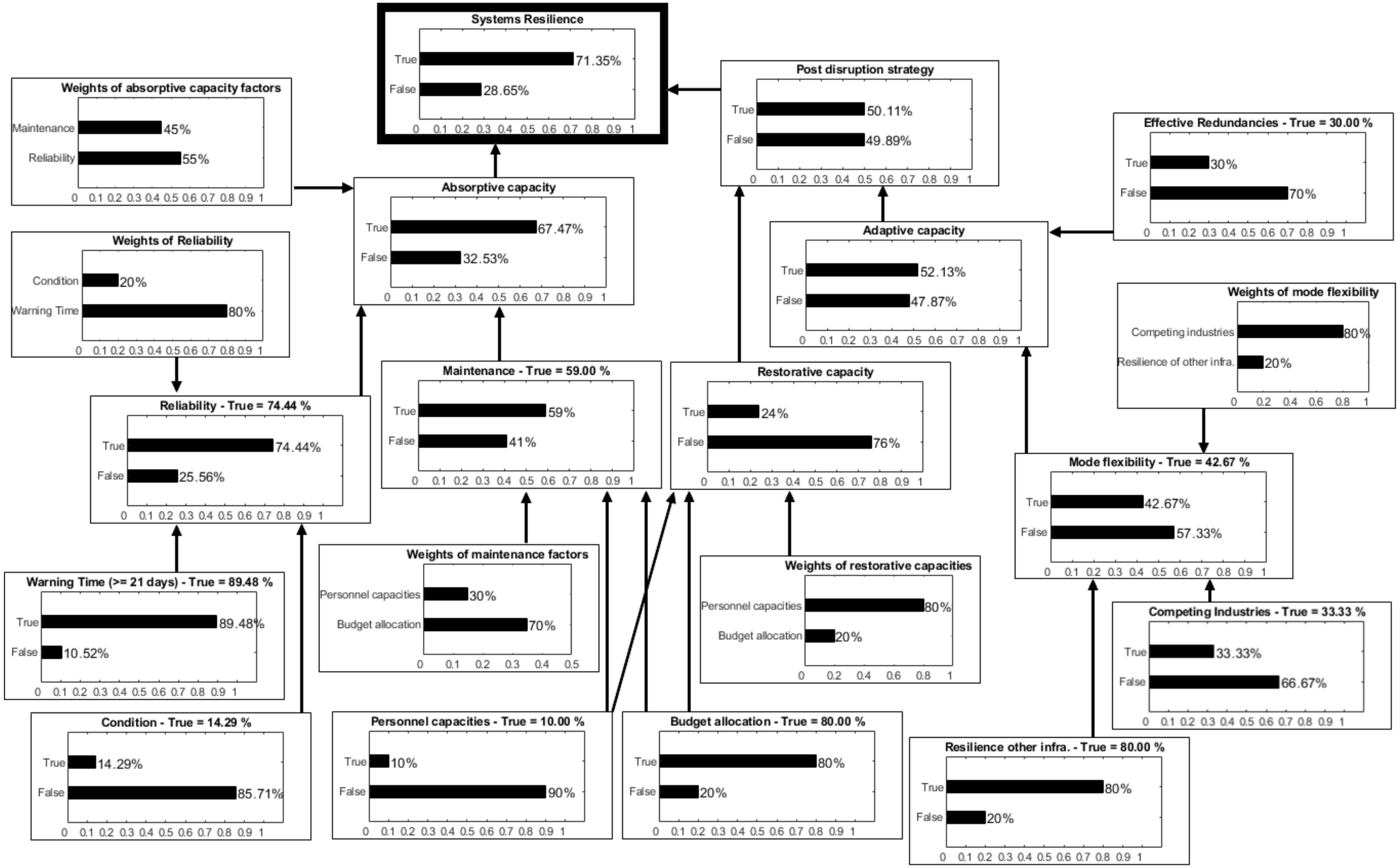

Figure 4.10: Updated Bayesian Network
(cf. Figure E.15)

The benefit for situation awareness is observed qualitatively within the scope of post-game discussions and evaluated by a post-game questionnaire. Figure 4.11 shows the affiliated results.

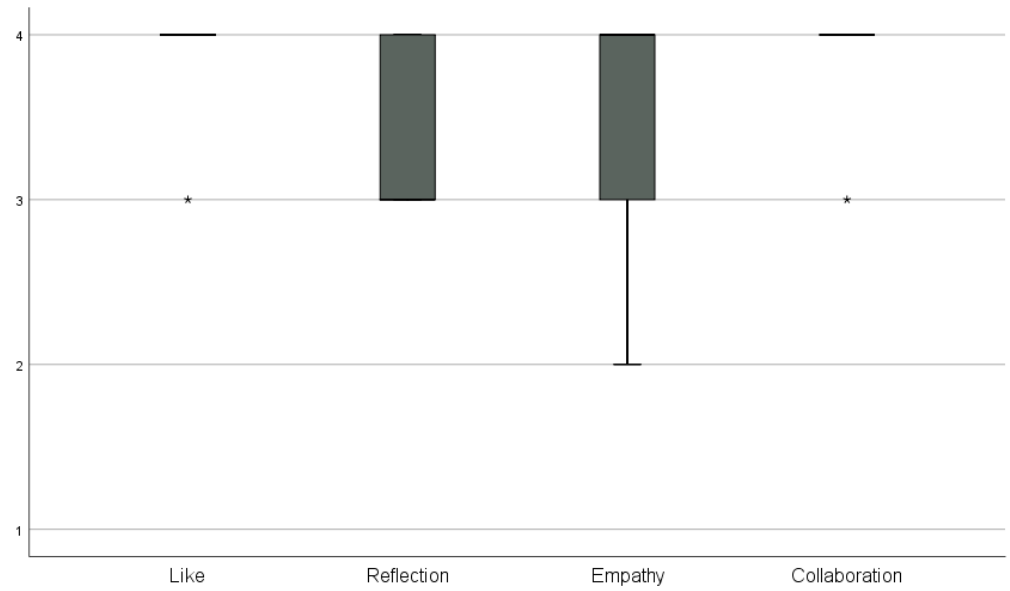

Figure 4.11: Evaluation of Post-game questionnaire
(cf. Figure E.16)

All players enjoyed the game (*Like*) while they felt challenged to reflect on the real-world system and their associated roles (*Reflection*). This implies a contribution to situation awareness, with its essential components being reflection and experience. The results also reveal learning effects of observed interdependencies and among the finding of a consensus. Moreover, the players found the required *collaboration* to be constructive, leading to a transfer toward the real-world SoS: Stakeholders must be willing to share their knowledge and therefore be positively disposed toward a constructive exchange and knowledge elicitation.

To conclude, the results exhibit that the method of serious gaming requires a close alignment with the real-world system to enhance and exploit expert knowledge to the end of improved systemic decision making. Thus, study E demonstrates the potential of collaborative serious gaming as an emerging method that should be considered more in both research and practice, at least to raise situation awareness among stakeholders of CI and to create a dialogue of stakeholders.

Nevertheless, the qualitative character of the extracted expert knowledge must be recognized. Furthermore, future research must account for the need for more data-driven assessments. Thereby, the transfer of the results to the Bayesian Network must be subject to strict validation in further extensions and iterations. Repeated applications with different groups of participants can realize further extensions to address potential bias factors. At the same time, it is demonstrated that similar applications can be reduced in their effort for development and calibration by using both existing games and computer-based simulations.

4.6 Study F: Measuring and visualizing Systemic risks

The following section refers to the content of the article "Measuring systemic and cascading risk of transport infrastructure based on a systemic approach and input-output modeling using the example of waterways". This article was written in collaboration with Marcus Wiens and Frank Schultmann and has been submitted to a scientific journal (Wehrle, Wiens, and Schultmann, 2022b). The article is an extension of the previous published article of Wehrle et al. (2020).

4.6.1 Study Context and contributions

The study's objective is to assess systemic risks resulting from neglected repair measures of transport infrastructures under the reflection of cascading effects and the different subsystems of the SoS. This SoS comprises the systems of building structure, industry, and population. The holistic risk assessment is implemented as a GIS-based risk dashboard to support the analysis and implementation of risk-based maintenance strategies.

The study identifies the interconnected subsystems construction, industry, and population in an aggregated risk framework to quantify risks stemming from complex infrastructure interdependencies, using the example of waterways as a barely studied object of research within this context. However, understanding possible risks and consequences is vital due to the manifold interdependencies and potentially severe consequences such as threats to life and limb. Thus, study F develops a framework to assess risks that occur at different and interdependent levels, based on Wehrle et al. (2020).

The framework is based on the assumption of IWT as SoS, as illustrated by Figure 4.12 and described in the study. Thereby, the following steps lead to the evaluation of building-specific risks:

(1) Identification of potential failure scenarios
(2) Determination of functional criticalities (cf. section 2.1.4)
(3) Identification of affected levels (cf. Figure 4.12, based on functional failure)
(4) Risk assessment on identified levels
(5) Risk aggregation

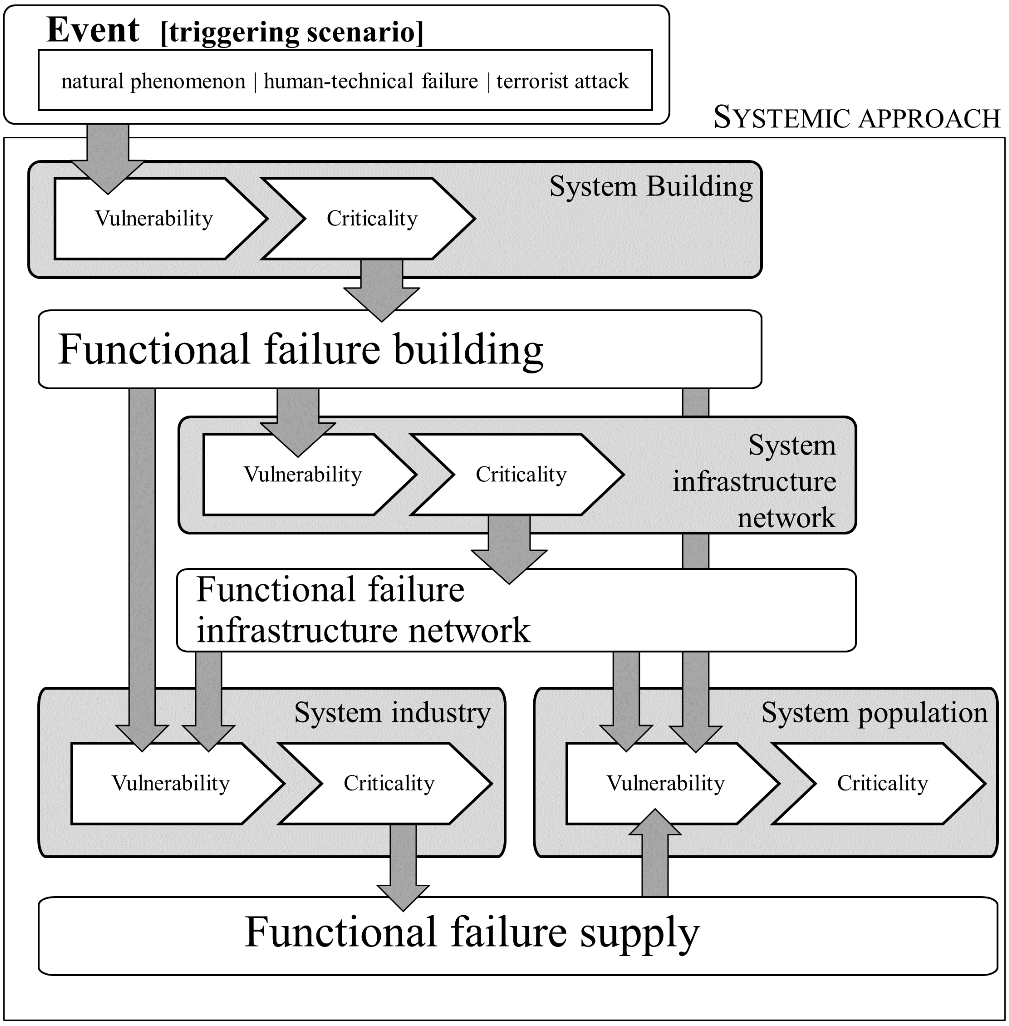

Figure 4.12: Systematic risk assessment of IWT as System-of-Systems (cf. Figure F.3)

The step *Risk assessment* comprises the vulnerability of building assets under consideration of scenario-based, system-inherent robustness, while assessment methodologies for the subsystems industry and population rely on assessing consequences in the event of failure. These comprise alternative routing and downtime costs, supply failures that affect the population via cascading effects, and the endangerment of human life due to the risk of flooding. To complete the risk assessment, the criticality is aggregated using a two-stage weighting procedure, reflecting risk aversion and goal prioritization of decision-makers.

The results are used and implemented in a risk dashboard built on editable databases. The dashboard provides a graphical and low-threshold interface and addresses the need for risk communication among stakeholders (cf. section 2.3.1). Therefore, it offers a quick view of the results and easily accessible background information. The risk dashboard can act as a foundation for a decision support tool for infrastructure operators to enable the integration of the developed approach into practicable decision processes and mechanisms.

Moreover, a particular account within the scope of risk assessment is given for the risk of interdependent CI, i.e., to analyze whether conceivable impacts on other CIs, which could result in cascading risks, may occur. Therefore, Inoperability Input-Output-Models (Ocampo et al., 2016; Santos and Haimes, 2004) are applied, whose fundamentals are described and summarized in the study. The proposed methodology is then applied to a use case of the WGCN.

Overall, the study Contributes a framework based on a chain of interdependent risks within the SoS waterways to the literature, whereas Input-Output-Modeling quantifies interdependencies of industries. A significant contribution is provided by the developed GIS-based decision tool, which depicts the spatial dimension and lowers barriers to applying risk-based maintenance strategies. A presentation of the main results and points of discussion of the study follows.

4.6.2 Results and Discussion

The results of study F comprise the structured identification of building-specific scenarios. For locks, the following are identified exemplarily: 1. Ice (heavy ice formation), 2. equipment (e.g. bollards) not functional, 3. stability of individual components is not given, 4. technical equipment in poor condition, 5. missing spare parts, 6. average, and, 7. sabotage/vandalism.

Table 4.2 shows the scenario assessment and risk evaluation for an exemplary lock. Figure 4.13 illustrates the developed risk dashboard and thus the potential of GIS-based applications for both risk communication and as a foundation for analysis and decision support tool, as it comprises the risk assessments of all infrastructure objects under consideration with simulated data.

The user interface is shown in Figure 4.13 and described within the study. It comprehensively incorporates all necessary functionalities, while the technical realization enables the potential to publish the tool on the intra- or internet.

Scenario	$\mathbf{Vuln.}_{b,s}$	$\mathbf{p}_{b,s}$	$\mathbf{Risk}_{Pop.,b,s}$	$\mathbf{Risk}_{Ind.,b,s}$	$\mathbf{u}_{b,s}$	$\mathbf{u}_{b,s} \times \mathbf{p}_{b,s}$	$\max\{\mathbf{u}_{b,s}\}$	$\mathbf{Risk}_{b}$
S1 – Ice	4.576	0.131	1.48	1.00	1.240	0.162	2.240	1.976
S2 – Equipment	4.538	0.130	1.48	3.00	2.240	0.290		
S3 – Stability	4.768	0.136	1.48	3.00	2.240	0.305		
S4 – Technical Eq.	4.678	0.134	1.48	2.00	1.740	0.233		
S5 – Spare parts	4.678	0.134	1.48	1.00	1.240	0.166		
S6 – Average	5.000	0.143	1.48	3.00	2.240	0.320		
S7 – Sabotage	4.753	0.136	1.48	2.00	1.740	0.236		

Table 4.2: Exemplary risk calculation

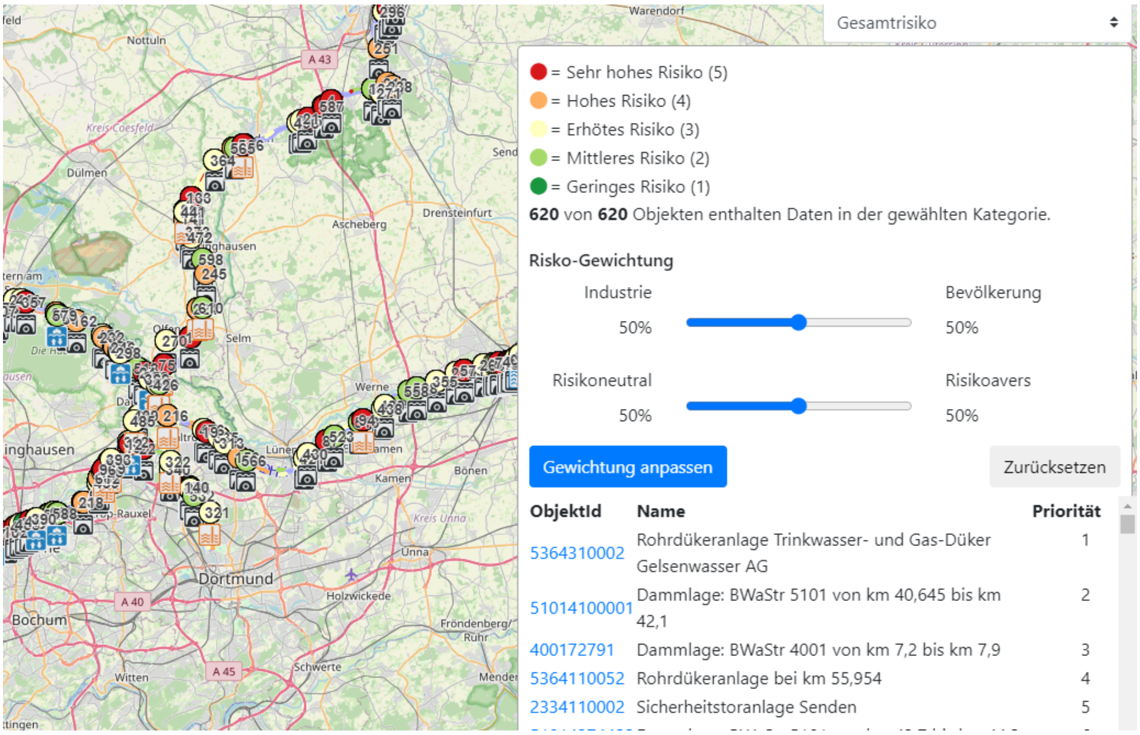

Figure 4.13: Layers and prioritizing
(cf. Figure F.9)

The examination of interdependent CIs reveals more findings on potential cascading effects compared to the mere assessment of buildings while power and water supply as dependent industries are under focus. Thereby, for the modeling region, it could be shown that drinking water stemming from surface water constitutes only 16.8% of water sources, while coal transport and still depending power supply are of greater significance in the area under consideration. Nevertheless, energy transition must be considered here in the future scope.

Cooling water is another interdependency that is considered within the interdependency analyses, with Figure 4.14 showing backward and forward linkages of all sectors, hence exhibiting shipping services as a solid backward linkage sector. This discovery means that IWT is not easily influenced by other sectors but can promptly influence the other sectors (Temursho, 2016). Further CI sectors are highlighted in the illustration and cascading effects are analyzed within the scope of the study. However, the results of the case study exhibit that impacts from cascading effects are negligible in terms of critical supplies for the examined case. Nevertheless, different problem constellations for other use cases or future developments of the considered database can reveal possible critical threats resulting from the analyzed interdependencies.

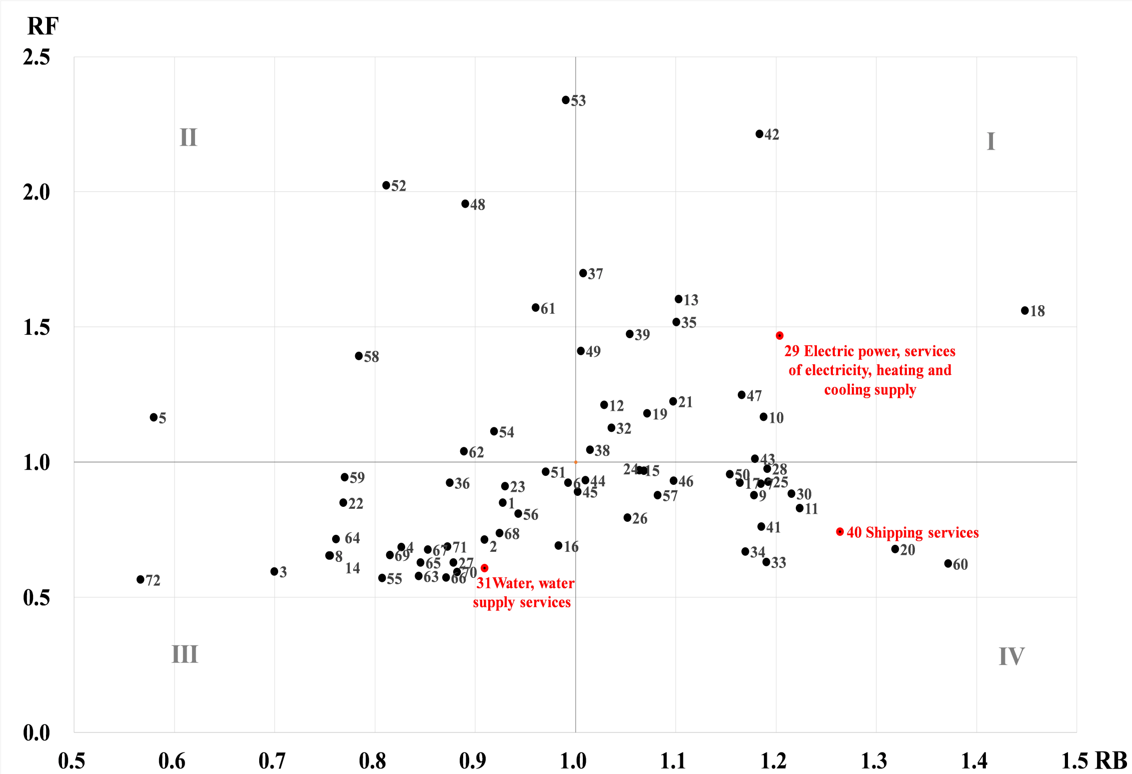

Figure 4.14: Backward and forward linkages of sectors
(with effect index RB and sensitivity RF, cf. Figure F.12)

To summarize, study F provides quantified in-depth analyses of the close interconnection of the SoS with its subsystems. The results highlight potentially severe impacts on industry and population if those responsible neglect or misallocate maintenance measures. Nevertheless, the observations suggest potential cascading effects to pose a comparatively low risk in the considered case study.

Overall, the need for and the potential of rather risk-based than time-oriented maintenance of infrastructure assets in order to avoid potential damage and reduce impacts becomes obvious. Moreover, the integration of risk assessment and GIS-based decision support tools as application in maintenance management with a high level of usability and decision transparency is shown to be of great significance for future developments in maintenance planning.

Limitations arise from the study's focus on the framework and impacts on interdependent CIs, while the precise assessment methods are explored in more depth elsewhere. Moreover, future contributions should include a calibration of the suggested weighting for goal-prioritizing, an implementation of the risk dashboard as a public authority-wide application, and the accounting for data protection.

4.7 Study G: Potential of infrastructure funds

The following section refers to the content of the article "Evaluation of the potential of infrastructure funds using the case of inland waterways". This article was written in collaboration with Marcus Wiens and Frank Schultmann and has been submitted to a scientific journal (Wehrle, Wiens, and Schultmann, 2022a).

4.7.1 Study Context and contributions

The study's objective is to assess the WTP for potential infrastructure funds for IWs and the benefits that could arise thereby. Thus, the literature review in the article outlines the literature and theory on infrastructure funds, comprising the conceptualization of WTP based on the assumption of transport infrastructure as a public good. To analyze this with regard to German IW's, study G uses an online survey to analyze the WTP and influencing variables using multivariate regressions and different fund mechanisms.

Therefore, requirements for the fund mechanisms are derived and are concluded to avoid rivalry with other departments within the budget. Furthermore, assumptions and prerequisites concern the state to be the initiator of the funds, an efficient reporting system, and central data processing. Study G uses a framework of a 2-stage decision process depicted in Figure 4.15, illustrating the differences in analyzed funds mechanisms for Fund 1, Fund 2, and Fund 3 (F1, F2, F3). Hence, F1 and F2 aim to primarily increase the current public budget with various private coverage (PC) mechanisms since not only investments into infrastructure maintenance but also those to PC in the event of flooding of private investors are considered. F3 aims additionally to address current problems in infrastructure maintenance 2.2.4 with the assumption of being implemented by a credible third party. The corresponding survey is conducted online and is structured in the following parts: 1. Introduction 2. Likert scaled questions 3. Query of WTP 4. WTP with group assignment 5. Socio-demographic questions.

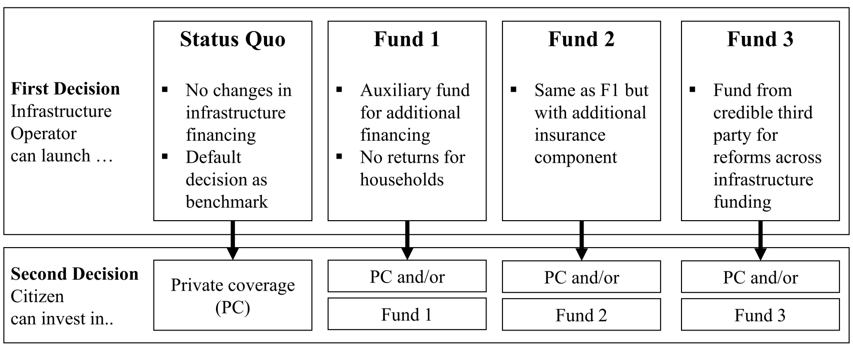

Figure 4.15: Decision Framework
(cf. Figure G.7)

While the Likert scaled questions aim to analyze the respondents' risk perception (cf. section 2.3.2), they could freely enter a value in Euros when questioned for their WTP. The protocol assigned participants randomly in one out of four groups, setting them in a scenario regarding their employer and their housing distance to the nearest IW, according to Table 4.3. The study closes with multivariate regressions for each fund to elaborate on influencing factors of the respective WTP.

		Housing – distance to the nearest IW	
		Short	70 km
Employer	High dependence on IWs	Group 1	Group 3
	Independent of IWs	Group 4	Group 2

Table 4.3: Grouping matrix
(see also Table G.1)

Overall, the study contributes to the body of literature by examining the WTP and the benefits of potential IFs by integrating empirical studies and focusing on IWs as a rarely considered field of application. Influencing factors of the WTP are analyzed and validated, which provides new insights into the risk perception of IWs. A case study among the German IWs contains a survey conducted from April 2021 to June 2021, resulting in 113 completed questionnaires. A presentation of the main results and points of discussion of the study follows.

4.7.2 Results and Discussion

The results of study G exhibit high standard deviations of WTPs, while the median value for PC is evaluated to be 0 EUR. Nevertheless, a general WTP for the public good is measurable with means of 29EUR (45 EUR; 18 EUR) for F1 (F2; F3), contradicting theoretically expected behavior according to a game-theoretical benchmark, but is consistent with behavior measured in comparable experiments. The WTP for F3 exhibits the lowest mean value but indicates a more reliable estimation, whereas the low WTP could be explained by the fact that the objectives are perceived as too general. Compared to the values of WTP of Entorf and Jensen (2020), the WTPs turn out to be lower, while the low awareness about IWs may be one influencing factor. The results also indicate that respondents trust the insurance component of F2 less than the option for PC or exploit the insurance coverage.

The results of the repeated measure after group assignment imply that the group assignment affects WTP differently in terms of specific WTP and direction of effect, as Figure 4.16 shows the WTP broken down by groups for the different funds.

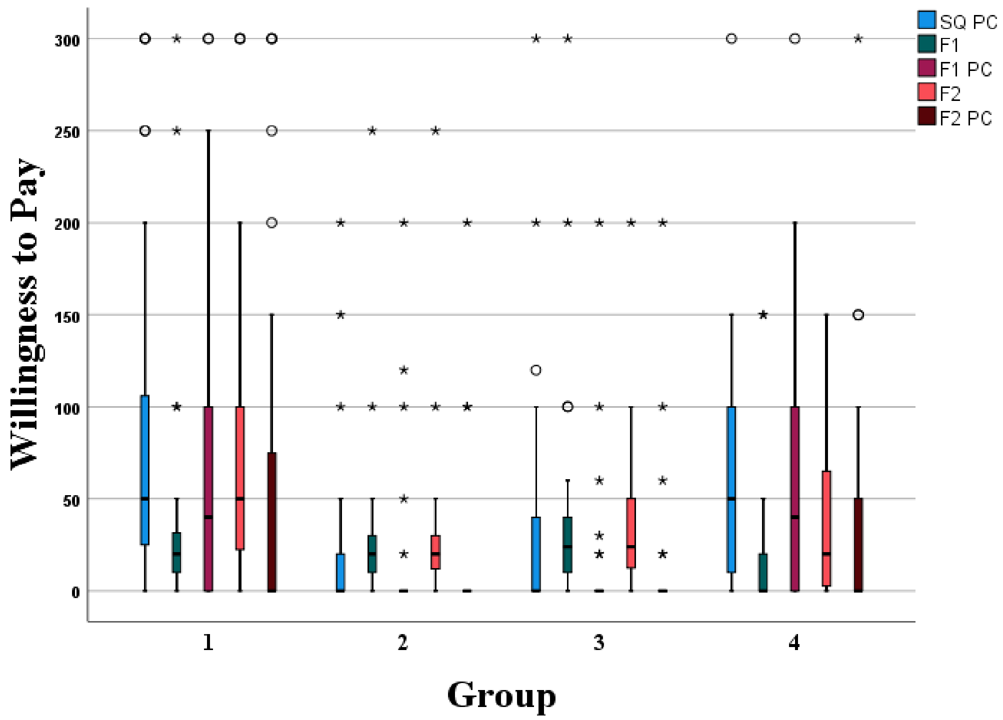

Figure 4.16: Willingness to Pay broken down by groups
(14 Data points not displayed with WTP >499, cf. Figure G.10)

Analyses of hypotheses additionally exhibit that the WTP for F2 is marginally higher than for F1. In contrast, other hypotheses could not be confirmed, e.g., that doubts about the WTP of others have a significant influence on one's WTP, addressing the free-rider problem (cf. section 2.2.4). However, ranked influencing factors are depicted in Figure 4.17, exhibiting that "Distance to waterway" has the highest average influence on WTP, which is followed by "Housing relationship" and "Confidence in the effective use of funds", "Return on fund" (3.8), "Being affected in the past" and "Doubts about others' WTP". Further results provide insights into the public perception of IWs and suggest a lack of awareness among the population, which could be reasoned in disinterest, missing perceived relevance, or too high complexity of the topic.

The regression models use the inclusion method and examine only a few explanatory variables for each fund. The coefficients for F1 and F2 differ, while past affectedness by floods, gender, and household income have a significant influence. For F1, the threat to one's existence, individual economic locations, and society are additionally significant. Household size, place of residence (urban, rural), and home ownership have no significant influence on the regressions.

To summarize, results show that house ownership and the distance of the residence to the waterway are crucial for the WTP in IFs, while funds with different designs show different levels of WTP. It is implied that governmental fund initiatives to improve infrastructure financing in Germany can be beneficial since households can finance the funds. Thus, a fund can most probably generate an improvement in the overall situation. Nevertheless, specific knowledge about waterways and

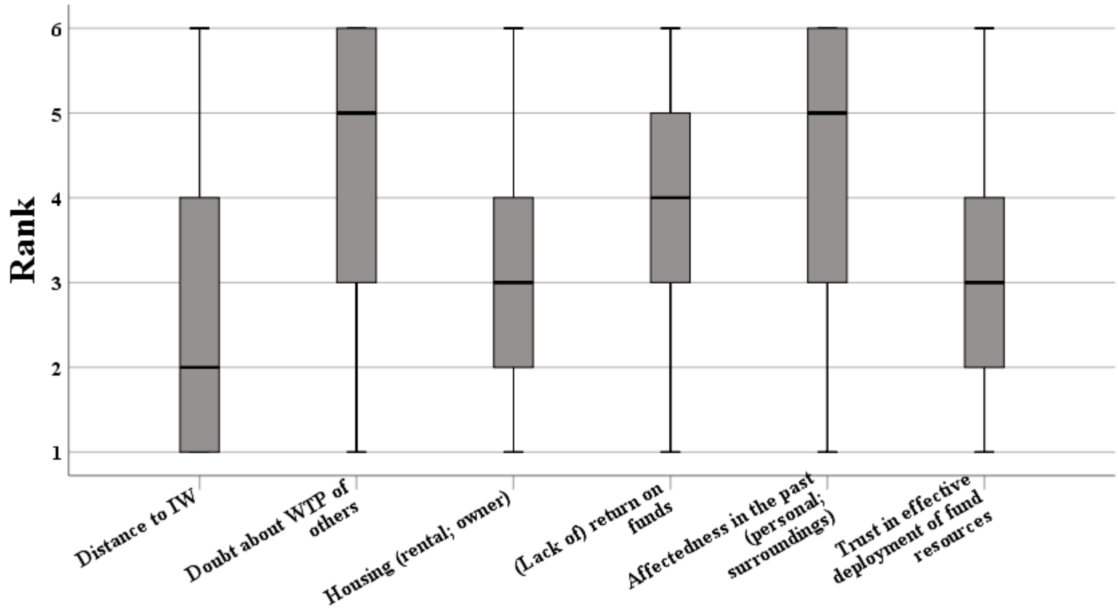

Figure 4.17: Ranking of influencing factors
(high rank=low rating, cf. Figure G.11)

IFs among the population should be enhanced and could increase the corresponding WTP and thus the funding security of infrastructure maintenance measures. Moreover, this contribution implies the potential of IFs as they pose the opportunity to control available resources in a targeted manner controlled by a third party, which could enable the planning security for resilience-based maintenance strategies.

Limitations include the hypothetical character of both WTP and hypothetical questions, whereas repeated surveys could account for potential biases. Furthermore, the scarcely studied field of research implies a lack of comparative analyses and values. Nevertheless, this analysis takes a first step toward an empirically based feasibility study of an infrastructure fund.

5 Managerial and Policy Implications

After recapitulating the study results, the following subsections summarize the management implications for the addressed decisions regarding a resilience-based maintenance strategy for IWs. While some implications hold across stakeholders, specific implications can be devoted to SCRM processes, maintenance management, funding, and risk communication, according to section 3.3.

5.1 Supply chain risk management

Studies A, B, C and D provide instructive insights into the mechanisms of SCRM and dependencies towards infrastructure availability. Examining both IWs as scarcely considered field of research, yet important mode of transportation and company decisions lead to managerial implications that should be seriously considered within the scope of SCRM of primarily manufacturing industries.

Study A demonstrates the assessment of the availability and reliability of IW systems which can find application within the field of logistics in the scope of SCRM. Hence, historical data should be collected to consider the development of public infrastructure conditions, which the dependent industries cannot influence.

Study B highlights the need to account for warning times regarding closures of infrastructure assets. Scopes of action must be held sufficiently flexible and agile concerning the critical early warning period, whereas communication with responsible authorities could ensure an adequate flow of information.

Study C sheds light on location preferences and underlines the managerial implications derived from the previous studies. Moreover, the need for communication with those responsible for infrastructure maintenance becomes obvious. The possibility of risk coping strategies and barriers to modal shift must be well examined.

Study D moreover provides insights into critical thresholds of availability and transport costs regarding the trade-off between modal shifts and the relocation of whole facilities. One managerial implication is that SCRM must consider the suggested evaluations, shedding light on the potential of relocating facilities. Nevertheless, this should only pose the very last option within the scope of action since a collaboration of all stakeholders involved should avoid resource-intensive outsourcing.

Overall, SC planning must account for key parameters such as conditions, availabilities, and notification times of infrastructure assets. Critical thresholds of those parameters must be known. Summarizing the findings of all the studies means that SCRM must exhaust all possibilities to be able to counter external risks. SC managers must ensure awareness of transportation risks, presence and quick accessibility of strategies to maintain SC resilience. Continuous communication with those responsible for transportation infrastructure must be established and assured. Nevertheless, SCRM cannot provide sufficient infrastructure conditions and thus can only react to the decisions of other stakeholders. Albeit, communication and collaboration are the only way to ensure compliance of own and collective economic and ecologic interests.

5.2 Maintenance management

All presented studies aim to contribute directly or indirectly toward implications and improvement of maintenance management. Direct contributions which allow deriving managerial implications for those responsible for infrastructure maintenance management comprise studies C, D, E, and F.

Detailed implications include those from study C, which comprise that the timeline of infrastructure failure makes a difference to business decisions and perceptions. Hence, maintenance management must consider the significance of the warning time before infrastructure closures towards manufacturing companies. Criticality mainly arises from short warning times, whereas sufficient capacities on other modes of transportation must compensate long-duration closures. Nevertheless, only a long-term perspective of reliable infrastructure can preserve business locations, as also study D underlines. Prioritizing maintenance measures and assessing the economic criticality of infrastructure failures must regard critical thresholds of availability.

Study E highlights even more the need for a resilience-based maintenance strategy since it demonstrates the suffering of current conditions as became evident by the extracted expert knowledge. Managerial implications comprise the need for enhancing situation awareness, while serious gaming is a powerful tool to do so. Moreover, resilience assessment should be applied and approved to make extensive use of the large amount of data already collected by public authorities.

Study F furthermore highlights the need to consider risk and resilience as holistic and interdisciplinary concepts requiring an interdisciplinary team of experts and evaluating potential cascading effects to assess the prioritization of maintenance measures under the consideration of scarce resources. Moreover, the study provides a powerful tool with the GIS-based application, leading to the managerial implication of applying this to infrastructure asset management to exploit its presented potential.

Overall, maintenance strategies for infrastructure should be more resilience-based than based on time-fixed schedules to avoid potential damage and reduce impacts. Available data should be used efficiently and considered in a holistic and interdisciplinary way before results must be processed in a reasonable yet understandable manner. Especially study D shows very clearly that resilience-based maintenance management goes beyond mere infrastructure planning. As stakeholder interviews in the PREVIEW research project (for Digital and Transport, 2018) have shown, the exit option of companies in the form of relocation is not an unrealistic threat. Risk-based maintenance is thus an essential prerequisite for regional attractiveness for companies and thus of high relevance for the business location. Knowledge of industrial linkages are of indispensable relevance to this end. Infrastructure managers and their processes should therefore continually reflect in their decisions and simultaneously evaluate how their decisions interact with the perceptions and decisions of the riparian industry. The need to apply the concept of TCO in maintenance planning thus is revealed once more since one significant cost factor lies in the potential loss of industrial sites. Thereby, it becomes apparent that risk perception which determines (presumed) acceptable risks must be put into relation to actual company decisions to predict the impact of infrastructure investments on corporate decisions.

5.3 Risk communication

Studies E, F and G enable the derivation of recommendations for courses of action in the field of risk communication. Thereby, study E highlights the need for interactive collaboration and emphasizes the potential of serious gaming as both a research tool and an opportunity to improve risk communication across stakeholders allowing for transparency and scrutiny of internal and cross processes. Both are essential in order to collaborate towards a functioning and resilient infrastructure. Hence, general stakeholder implications comprise that the application of collaborative serious gaming should be considered more in the environment of maintenance planning, thus creating Situation Awareness among stakeholders of CI and approaches for improved cooperation.

Study F supports the need for risk communication by a GIS-based application allowing for the visualization of localized buildings in their local landscape with their associated risk assessment. Accompanying explanations and a user-friendly interface allow easy operation and promise minimal hurdles for users. Facilitated risk communication between all stakeholders promises the possibility of involving interdisciplinary experts to validate the risk assessment and determine action prioritization based on resilience-based maintenance strategies. Hence, the implication is to further develop the GIS-based tool with the aim of applying it across stakeholders.

Study G sheds light on the importance of risk communication toward the population. Hence, infrastructure operators and owners must account for the insufficient knowledge about waterways and infrastructure funds among the German population. This knowledge should be enhanced, which offers multiple relevance: The population understands the infrastructure of their surroundings, which promotes technical know-how, but also familiarity and competence regarding risks and potentials. This, in turn, is a prerequisite for the acceptance of a fund and can promote both the willingness to participate and the WTP.

Overall, risk communication concerns all stakeholders, while serious gaming and GIS applications should be considered more in the environment of maintenance planning, thus aiming to exploit their respective potential. However, the consideration of both organizational and individual risk perception plays an essential role in risk communication. Supporting tools as those presented should not be underestimated, including their contribution to the scientific acquisition and deployment of data and models. Since interactive formats encourage stakeholders to be activated, more direct communication is made possible here than is the case with usual discussion rounds, where oftentimes rehearsed points of view and one-sided demands are repeated. Instead, the stimulation of the stakeholders' creativity center is achieved. Visual and playful approaches simultaneously address creativity and reflection of the real-world frame of reference. Once this is experienced in a safe environment, this style of interdisciplinary risk communication discloses hidden potentials of active participation.

5.4 Funding

Study G is the only one that directly addresses funding as well as the assumption of underfunding. It explicitly reveals that applying the TCO concept is necessary to target existing resources as part of a resilience-based maintenance strategy. Measures must be effectively evaluated and prioritized by directly contrasting benefits and threats. Only in this way can scarce resources be optimally utilized in the long term. However, the identified multifaceted problem construct in infrastructure funding and alongside mechanisms must be continually diminished.

The deliberation of different fund possibilities illustrates the considerable potential and implies the necessity of greater attention for this type of financing. Furthermore, it must be examined whether the government, in its unique task of providing services of general interest, can handle the problems of infrastructure maintenance on its own. Otherwise, a third party, e.g., a funds donor (as opposed to paid consultants), could bring about efficient improvements here.

Nevertheless, the remaining studies point out that those responsible should consider the effect of their infrastructure investment decisions on local areas' attractiveness as business location. This is a direct conclusion from the necessary condition of a resilience-based maintenance strategy, which must cover all dimensions of risk.

6 Conclusion

6.1 Summary

Transport infrastructure is characterized by a mesh of risks consisting of a poor state of infrastructure, a systemic maintenance backlog, and a predominating lack of resources. Therefore, infrastructure owners and operators must allocate resources optimally to avoid risks resulting in a decrease in reliability and a reduction in resilience. This allocation of measures in asset management requires the identification of system-critical elements. Meanwhile, the concept of TCO must find application, accounting for the need to offset infrastructure investment against the costs of neglected maintenance.

The dissertation contributes to the literature with the help of seven studies with the overall purpose of enhancing measurement and communication of CI criticality, considering the significance of transport infrastructure for business locations, the different stakeholders involved, and the little-studied yet significant example of waterways Figure 6.1 recapitulates the topic-specific arrangement of the studies once again in a structured manner.

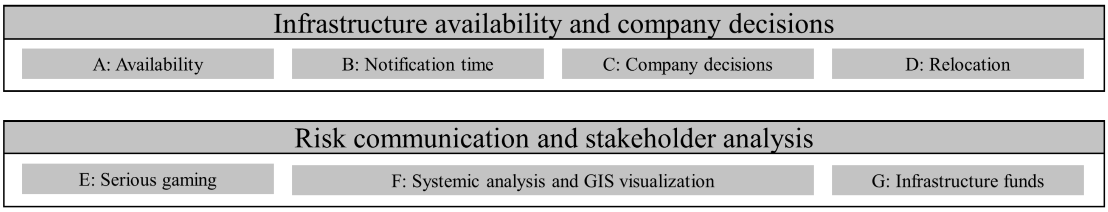

Figure 6.1: Contributions of the present dissertation: structured studies

Meanwhile, the first sample primarily contributes to understanding company decisions resulting from neglected infrastructure maintenance measures. Moreover, it provides measures for the significance of transport infrastructure for business locations. Thus, primarily the identification of system-critical elements is addressed as well as the promotion of significant steps toward an integrated application of the TCO concept. Study A and B thus shed light on internal SCRM processes of manufacturing industries, while study C and D enlarge the focus to deriving the economic criticality of misallocated maintenance resources. Thus, they reflect the necessity of resilience-based maintenance management and exhibit the potential of demonstrated methods. Furthermore, one of the most important findings is that the relocation of facilities due to infrastructural shortcomings is not an unrealistic threat that collaborative efforts of all parties involved must encounter. Hence, the combined consideration of risk perception, determining acceptable risks, and actual company decisions enables the prediction of industrial responses to infrastructure failures. The relationship between infrastructure availability and relocations and their connection across critical thresholds represents a significant transition in the perception and assessment of the criticality of infrastructure networks, the consideration of which has been scarce in the literature so far.

The second sample of studies serves primarily the purpose of prioritizing and enabling maintenance measures and enhancing stakeholder communication. Besides prioritizing problems, general funding problems and alongside mechanisms are addressed by study G, after study E and F account for the need for enhanced risk communication. Hence, study E applies serious gaming to elicit expert knowledge and strengthen collaboration. Study F then exhibits the benefit of GIS-based visualizations of an integrated risk assessment of IW buildings. It becomes evident that risk perception and risk communication significantly influences stakeholder awareness, which needs to be promoted continuously. Interactive formats in safe environments contribute to the exploitation of experts knowledge and expertise on their risk perception. The confrontation with a realistic image of the real-world provides insight into discrepancies between modeling and predetermined and lived processes of the stakeholders, that largely determine the resilience of the overall infrastructure system.

Derived managerial implications affect the processes of SCRM, maintenance management, risk communication, and funding. Consequently, the studies contribute to an increase in the resilience of IWs under their consideration as complex SoS. The application of TCO proves to be an indispensable concept in infrastructure planning. The determined criticality must incorporate potential losses from relocated facilities in case of neglected infrastructure maintenance. Hence, the foundation of a resilience-based maintenance strategy was established as a method for assessing, visualizing and thus communicating measure prioritization is presented. Altogether, it becomes apparent that researchers should investigate emerging research tools and interactive concepts together with stakeholder representatives. Active participation in new and innovative formats that link science and practice promotes mutual benefits: researchers gain insights into stakeholder processes and perceptions, while the development of practical tools needs to integrate stakeholder knowledge and requirements. Stakeholders from industry, executive agencies, and governmental leadership levels attain an appreciation of their personal and institutional contribution both in research and in multi-lateral dialogue with all responsible parties. Collaborative formats thereby increase the sense of working together for a common task, whereas traditional formats such as panel discussions usually only repeat entrenched goals and viewpoints of individual institutions.

6.2 Outlook

The present dissertation contributes many starting points for a holistic resilience-based management of transport infrastructures. Especially waterways will become increasingly important in the future under the reflection of a desired environmentally friendly modal shift (cf. section 2.1.1). Therefore this subsection offers implications for future research potentials.

Limitations comprise the finalized application of TCO as aggregated and applicable methodology to assess quantified and aggregated monetary values. Albeit this dissertation provides significant contributions toward a holistic evaluation of costs for risks, all dimensions of risk must be aggregated and validated and must be offset against costs for vulnerability increases by maintenance measures. Nevertheless, the present dissertation clearly showed that this is possible fundamentally. Thus, one can exemplarily extend study F by more specific monetary investigations, whereas the results of study D can serve to assess expected cost increases.

Future research should attempt to integrate the scheduling of maintenance resources since this dissertation outlined the great importance and severe impact of a lack of resources. However, just increases in the budget cannot solve the structural problems as a lack of money does not equate to a lack of staff. Integrated resilience-based maintenance schedules thus must incorporate personnel capacities. Subsequent research should aim to optimize resource allocation (scheduling) and stakeholder processes.

Improvements in internal and external stakeholder processes to enable improvements in practice should be tackled simultaneously since these offer lots of potential for collaboration and avoid duplicate or opposing efforts. While collaborative formats of interdisciplinary workshops can achieve process analysis, effective optimization potential must account for the necessity, the effort of adaptation, and the acceptance of the executing employees. Overall, this highlights the role of researchers as they bear joint responsibility for continuously adapting maintenance strategies to new challenges and effectively transferring knowledge between science and practitioners.

Moreover, the potential and feasibility of infrastructure funds must be analyzed. Thereby, fund mechanisms should be aligned with the principles of TCO to deploy existing resources in a trustworthy and effective manner.

Bibliography

Alcaraz, C., Zeadally, S. (2015). Critical Infrastructure Protection: Requirements and Challenges for the 21st Century. *International Journal of Critical Infrastructure Protection*, *8*, 53–66.

Allah Bukhsh, Z., Stipanovic, I., Klanker, G., O' Connor, A., Doree, A. G. (2019). Network Level Bridges Maintenance Planning using Multi-Attribute Utility Theory. *Structure and Infrastructure Engineering*, *15*(7), 872–885.

Altherr, L. C., Leise, P., Pfetsch, M. E., Schmitt, A. (2019). Resilient Layout, Design and Operation of Energy-Efficient Water Distribution Networks for High-Rise Buildings using MINLP. *Optimization and Engineering*, *20*(2), 605–645.

An, S., Cui, N., Bai, Y., Xie, W., Chen, M., Ouyang, Y. (2015). Reliable Emergency Service Facility Location under Facility Disruption, En-Route Congestion and In-Facility Queuing. *Transportation Research Part E: Logistics and Transportation Review*, *82*, 199–216.

Arunraj, N. S., Maiti, J. (2007). Risk-Based Maintenance—Techniques and Applications. *Journal of Hazardous Materials*, *142*(3), 653–661.

Aven, T., Ylönen, M. (2018). The Enigma of Knowledge in the Risk Field. In T. Aven E. Zio (Eds.), *Knowledge in Risk Assessment and Management* (Vol. 33, pp. 27–47). Hoboken, NJ: John Wiley & Sons Inc.

Ayyub, B. M. (2003). *Risk Analysis in Engineering and Economics*. Boca Raton, Fla.: Chapman & Hall/CRC.

Ayyub, B. M. (2014). Systems Resilience for Multihazard Environments: Definition, Metrics, and Valuation for Decision Making. *Risk Analysis: An official Publication of the Society for Risk Analysis*, *34*(2), 340–355.

Bagheri, E., Ghorbani, A. A. (2010). UML-CI: A Reference Model for Profiling Critical Infrastructure Systems. *Information Systems Frontiers*, *12*(2), 115–139.

Baghersad, M., Zobel, C. W. (2015). Economic Impact of Production Bottlenecks caused by Disasters Impacting Interdependent Industry Sectors. *International Journal of Production Economics*, *168*, 71–80.

Bardt, H., Chrischilles E., Fritsch M., Grömling M., Puls T., Röhl K.- H. (2014). Die Infrastruktur in Deutschland: Zwischen Standortvorteil und Investitionsbedarf: IW-Analysen. (95).

Baroud, H., Ramirez-Marquez, J. E., Barker, K., Rocco, C. M. (2014). Stochastic Measures of Network Resilience: Applications to Waterway Commodity Flows. *Risk Analysis : An Official Publication of the Society for Risk Analysis*, *34*(7), 1317–1335.

Behrendt, F., Trojahn, S. (2013). Herausforderung für die Zukunft - nachhaltige und solide Verkehrsinfrastrukturfinanzierung. *18. Magdeburger Logistiktage - Sichere und nachhaltige Logistik*.

Biringer, B. (2013). *Critical Infrastructure System Security and Resiliency*. Hoboken: CRC Press.

Blackhurst, J., Rungtusanatham, M. J., Scheibe, K., Ambulkar, S. (2018). Supply Chain Vulnerability Assessment: A Network Based Visualization and Clustering Analysis Approach. *Journal of Purchasing and Supply Management*, *24*(1), 21–30.

Boloori Arabani, A., Farahani, R. Z. (2012). Facility Location Dynamics: An Overview of Classifications and Applications. *Computers & Industrial Engineering*, *62*(1), 408–420.

Buldyrev, S. V., Parshani, R., Paul, G., Stanley, H. E., Havlin, S. (2010). Catastrophic Cascade of Failures in Interdependent Networks. *Nature*, *464*, 1025–1028.

Button, K. J., Leitham, S., McQuaid, R. W., Nelson, J. D. (1995). Transport and Industrial and Commercial Location. *The Annals of Regional Science*, *29*(2), 189–206.

Cabinet Office. (2011). *Keeping the Country Running: Natural Hazards and Infrastructure — A Guide to Improving the Resilience of Critical Infrastructure and Essential Services*. London. Retrieved 03.05.2022, from `https://www.gov.uk/government/publications/keeping-the-country-running-natural-hazards-and-infrastructure`

Cavalcante, I. M., Frazzon, E. M., Forcellini, F. A., Ivanov, D. (2019). A Supervised Machine Learning Approach to Data-Driven Simulation of Resilient Supplier Selection in Digital Manufacturing. *International Journal of Information Management*, *49*(3), 86–97.

CE Delft (Ed.). (2017). *STREAM Freight transport 2016: Emissions of freight transport modes*. Delft, Netherlands.

Chae, K. C., Clark, G. M. (1986). System Reliability in the Presence of Common-Cause Failures. *IEEE Transactions on Reliability*, *35*(1), 32–35.

Chatti, K., Zaabar, I. (2012). *Estimating The Effects of Pavement Condition on Vehicle Operating Costs* (Vol. 720). Washington, D.C.: Transportation Research Board.

Cheaitou, A., Hamdan, S., Larbi, R., Alsyouf, I. (2021). Sustainable Traveling Purchaser Problem with Speed Optimization. *International Journal of Sustainable Transportation*, *15*(8), 621–640.

Chee Wai, L., Wongsurawat, W. (2012). Crisis Management: Western Digital's 46–Day Recovery from the 2011 Flood Disaster in Thailand. *Strategy & Leadership*, *41*(1), 34–38.

Chen, L., Miller-Hooks, E. (2012). Resilience: An Indicator of Recovery Capability in Intermodal Freight Transport. *Transportation Science*, *46*(1), 109–123.

Chen, Y., v. Milanovic, J. (2017). Critical Appraisal of Tools and Methodologies for Studies of Cascading Failures in Coupled Critical Infrastructure Systems. In *IEEE EUROCON 2017* (pp. 599–604). Piscataway, New Jersey: IEEE.

Chowdhury, S., Zhu, J., Zhang, W. (2020). Optimized restoration planning of infrastructure system-of-systems using heterogeneous network flow simulation. *Journal of Computing in Civil Engineering*, *34*(5).

Christopher, M. (2016). *Logistics & Supply Chain Management* (5th ed.). Harlow, United Kingdom: Pearson Education.

Christopher, M., Peck, H. (2004). Building the Resilient Supply Chain. *The International Journal of Logistics Management*, *15*(2), 1–14.

Coetzee, Petrus J. van V., Swanepoel, P. A. (2017). Spatial Relationships and Movement Patterns of the Air Cargo Industry in Airport Regions. *Journal of Transport and Supply Chain Management*, *11*(0), 10.

Cooke, N. J. (1994). Varieties of Knowledge Elicitation Techniques. *International Journal of Human-Computer Studies*, *41*(6), 801–849.

Cooke, R. M., Goossens, L. H. J. (2004). Expert Judgement Elicitation for Risk Assessments of Critical Infrastructures. *Journal of Risk Research*, *7*(6), 643–656.

Craighead, C. W., Blackhurst, J., Rungtusanatham, M. J., Handfield, R. B. (2007). The Severity of Supply Chain Disruptions: Design Characteristics and Mitigation Capabilities. *Decision Sciences*, *38*(1), 131–156.

Crowther, K. G. (2008). Decentralized Risk Management for Strategic Preparedness of Critical Infrastructure Through Decomposition of the Inoperability Input–Output Model. *International Journal of Critical Infrastructure Protection*, *1*, 53–67.

Daehre, K.-H. (Ed.). (2012). *Zukunft der Verkehrsinfrastrukturfinanzierung: Bericht der Kommission.*

Debande, O. (2002). Private Financing of Transport Infrastructure an Assessment of the UK Experience. *Journal of Transport Economics and Policy*, *36*(3), 355–387.

de Bok, M. (2009). Estimation and Validation of a Microscopic Model for Spatial Economic Effects of Transport Infrastructure. *Transportation Research Part A: Policy and Practice*, *43*(1), 44–59.

Degraeve, Z., Roodhooft, F. (1999). Effectively Selecting Suppliers Using Total Cost of Ownership. *Journal of Supply Chain Management*, *35*(1), 5.

Department of Homeland Security (Ed.). (2016). *Critical Infrastructure Threat Information Sharing Framework: A Reference Guide for the Critical Infrastructure Community.*

DIN ISO 55000. (2014). *Asset Management: Overview, Principles and Terminology* (Tech. Rep.). BSI Standards Ltd.

Ding, S.-H., Kamaruddin, S. (2015). Maintenance Policy Optimization—Literature Review and Directions. *The International Journal of Advanced Manufacturing Technology*, *76*(5), 1263–1283.

Dolgui, A., Ivanov, D., Sokolov, B. (2018). Ripple Effect in the Supply Chain: An Analysis and Recent Literature. *International Journal of Production Research*, *56*(1-2), 414–430.

Ebeling, C. E. (2017). *An Introduction to Reliability and Maintainability Engineering* (21st ed.). New York, USA: McGraw-Hill.

Edelenbos, J., Klijn, E.-H. (2007). Trust in Complex Decision-Making Networks. *Administration & Society*, *39*(1), 25–50.

Elhadidy, A. A., Elbeltagi, E. E., Ammar, M. A. (2015). Optimum Analysis of Pavement Maintenance using Multi-Objective Genetic Algorithms. *HBRC Journal*, *11*(1), 107–113.

Ellingwood, B. R. (2005). Risk-Informed Condition Assessment of Civil Infrastructure: State of Practice and Research Issues. *Structure and Infrastructure Engineering*, *1*(1), 7–18.

Ellis, S. C., Henry, R. M., Shockley, J. (2010). Buyer Perceptions of Supply Disruption Risk: A Behavioral View and Empirical Assessment. *Journal of Operations Management*, *28*(1), 34–46.

Ellram, L. (1993). Total Cost of Ownership: Elements and Implementation. *International Journal of Purchasing and Materials Management*, *29*(3), 2–11.

Ellram, L. M., Siferd, S. P. (1998). Total Cost of Ownership: A Key Concept in Strategic Cost Management Decisions. *Journal of Business Logistics*, *19*(1).

Endsley, M. R. (1995). Toward a Theory of Situation Awareness in Dynamic Systems. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *37*(1), 32–64.

Entorf, H., Jensen, A. (2020). Willingness-to-Pay for Hazard Safety - A Case Study on the Valuation of Flood Risk Reduction in Germany. *Safety Science*, *128*, 104657.

European Commission. (2019). *Transport in the European Union: Current Trends and Issues*. Brussels. Retrieved 04.05.2022, from `https://www.nrso.ntua.gr/european-commission-transport-in-the-european-union-current-trends-and-issues-2019/`

Eusgeld, I., Nan, C., Dietz, S. (2011). "System-of-Systems" Approach for Interdependent Critical Infrastructures. *Reliability Engineering & System Safety*, *96*(6), 679–686.

Ezell, B. C. (2007). Infrastructure Vulnerability Assessment Model (I-VAM). *Risk Analysis : An Official Publication of the Society for Risk Analysis*, *27*(3), 571–583.

Farahani, R. Z., Drezner, Z., Asgari, N. (2009). Single Facility Location and Relocation Problem with Time Dependent Weights and Discrete Planning Horizon. *Annals of Operations Research*, *167*(1), 353–368.

Faturechi, R., Miller-Hooks, E. (2015). Measuring the Performance of Transportation Infrastructure Systems in Disasters: A Comprehensive Review. *Journal of Infrastructure Systems*, *21*(1), 04014025.

Federal Ministry for Digital and Transport (Ed.). (2014a). Sicherheitsstrategie für die Güterverkehrs- und Logistikwirtschaft: Schutz kritischer Infrastrukturen und verkehrsträgerübergreifende Gefahrenabwehr.

Federal Ministry for Digital and Transport (Ed.). (2014b). VV-WSV 1102 Objektkatalog: Verwaltungsvorschrift der Wasserstraßen- und Schifffahrtsverwaltung des Bundes.

Federal Ministry for Digital and Transport (Ed.). (2015). Verkehrsinfrastrukturbericht.

Federal Ministry for Digital and Transport (Ed.). (2016). Bundesverkehrswegeplan 2030.

Federal Ministry for Digital and Transport (Ed.). (2019). Masterplan Binnenschifffahrt.

Federal Ministry for Digital and Transport (Ed.). (2021). Verkehr in Zahlen 2020/2021. (47).

Federal Ministry of the Interior and Community (Ed.). (2009). Nationale Strategie zum Schutz kritischer Infrastrukturen: KRITIS-Strategie.

Federal Statistical Office of Germany (Ed.). (2021). *Beförderungsmenge und Beförderungsleistung nach Verkehrsträgern.* Retrieved 07.02.2022, from `https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Transport-Verkehr/Gueterverkehr/Tabellen/gueterbefoerderung-lr.html`

Fekete, A. (2011). Common Criteria for the Assessment of Critical Infrastructures. *International Journal of Disaster Risk Science*, *2*(1), 15–24.

Ferrin, B. G., Plank, R. E. (2002). Total Cost of Ownership Models: An Exploratory Study. *The Journal of Supply Chain Management*, *38*(3), 18–29.

Fichert, F. (2017). Transport Policy Planning in Germany - An Analysis of Political Programs and Investment Masterplans. *European Transport Research Review*, *9*(2).

Flyvbjerg, B., Skamris holm, M. K., Buhl, S. L. (2003). How Common and How Large are Cost Overruns in Transport Infrastructure Projects? *Transport Reviews*, *23*(1), 71–88.

Folga, S., Allison, T., Seda-Sanabria, Y., Matheu, E., Milam, T., Ryan, R., Peerenboom, J. (2009). A Systems-Level Methodology for the Analysis of Inland Waterway Infrastructure Disruptions. *Journal of Transportation Security*, *2*(4), 121–136.

for Digital, F. M., Transport. (2018). *Verbundforschungsvorhaben Resilienz kritischer Verkehrsinfrastrukturen am Beispiel der Wasserstraßen.* Retrieved from https://www.sifo.de/sifo/de/projekte/schutz-kritischer-infrastrukturen/verkehrsinfrastrukturen/preview-resilienz-kritischer-v-am-beispiel-der-wasserstrassen/preview-resilienz-kritischer-v-am-beispiel-der-wasserstrassen.html

Frangopol, D. M., Liu, M. (2007). Maintenance and Management of Civil Infrastructure Based on Condition, Safety, Optimization, And Life-Cycle Cost, pages = 29–41, volume = 3, number = 1, journal = Structure and Infrastructure Engineering, 1573-2479,.

Frerich, J., Müller, G. (2004). *Europäische Verkehrspolitik* (1. Aufl. ed., Vol. Band 1). München, Wien: Oldenbourg.

Fujimoto, T. (2011). *Supply Chain Competitiveness and Robustness: A Lesson from the 2011 Tohoku Earthquake and Supply Chain "Virtual Dualization".*

Gaillard, J. C. (2010). Vulnerability, Capacity and Resilience: Perspectives for Climate and Development Policy. *Journal of International Development*, *22*(2), 218–232.

Geekiyanage, D., Fernando, T., Keraminiyage, K. (2020). Assessing the State of the Art in Community Engagement for Participatory Decision-Making in Disaster Risk-Sensitive Urban Development. *International Journal of Disaster Risk Reduction : IJDRR*, *51*, 101847.

German Press Agency (dpa) (Ed.). (2019). *Sperrung von Wasserstraße: Millionenverluste befürchtet.* Retrieved 06.05.2022, from https://www.berlin.de/aktuelles/brandenburg/5731479-5173360-sperrung-von-wasserstrasse-millionenverl.html

Giannopoulos, G., Dorneanu, B., Jonkeren, O. (2013). *Risk Assessment Methodology for Critical Infrastructure Protection* (Vol. 25745). Luxembourg: Publications Office.

Gong, J., Mitchell, J. E., Krishnamurthy, A., Wallace, W. A. (2014). An interdependent layered network model for a resilient supply chain. *Omega*, *46*, 104–116.

Günneç, D., Salman, F. S. (2011). Assessing the Reliability and the Expected Performance of a Network under Disaster Risk. *OR Spectrum*, *33*(3), 499–523.

Haimes, Y. Y. (2008). Models for Risk Management of Systems of Systems. *International Journal of System of Systems Engineering*, *1*(1/2), 222.

Haimes, Y. Y. (2018). Risk Modeling of Interdependent Complex Systems of Systems: Theory and Practice. *Risk Analysis : An Official Publication of the Society for Risk Analysis*, *38*(1), 84–98.

Hansen, M., Sutter, J. (1990). *The Shake with Freight: The Impact of the Loma Prieta Earthquake on Bay Area Truckers. Working Paper* (No. UCTC No. 1). Retrieved from https://trid.trb.org/view/411653

Haraguchi, M., Lall, U. (2015). Flood Risks and Impacts: A Case Study of Thailand's Floods in 2011 and Research Questions for Supply Chain Decision Making. *International Journal of Disaster Risk Reduction*, *14*, 256–272.

Hashimoto, T., Stedinger, J. R., Loucks, D. P. (1982). Reliability, Resiliency, and Vulnerability Criteria for Water Resource System Performance Evaluation. *Water Resources Research*, *18*(1), 14–20.

Helm, D. (2009). Infrastructure Investment, the Cost of Capital, and Regulation: An Assessment. *Oxford Review of Economic Policy*, *25*(3), 307–326.

Henley, E. J., Kumamoto, H. (1981). *Reliability Engineering and Risk Assessment*. Englewood Cliffs, NJ: Prentice-Hall.

Holický, M., Diamantidis, D. (2014). *Methods for the Risk Assessment and Risk-Based Management of Aging Infrastructure* (1st ed. ed.). Prague: Czech Technical University in Prague, Klokner Institute.

Hossain, N. U. I., Nur, F., Hosseini, S., Jaradat, R., Marufuzzaman, M., Puryear, S. M. (2019). A Bayesian Network Based Approach for Modeling and Assessing Resilience: A Case Study of a Full Service Deep Water Port. *Reliability Engineering & System Safety*, *189*(1), 378–396.

Hosseini, S., Barker, K. (2016). Modeling Infrastructure Resilience using Bayesian Networks: A Case Study of Inland Waterway Ports. *Computers & Industrial Engineering*, *93*(7), 252–266.

Hosseini, S., Ivanov, D., Dolgui, A. (2019). Review of Quantitative Methods for Supply Chain Resilience Analysis. *Transportation Research Part E: Logistics and Transportation Review*, *125*, 285–307.

Houlihan, B. (1994). Europe's Ageing Infrastructure. *Utilities Policy*, *4*(4), 243–252.

Huth, M., Romeike, F. (Eds.). (2016). *Risikomanagement in der Logistik: Konzepte - Instrumente - Anwendungsbeispiele* (1st ed.). Wiesbaden: Springer Gabler.

Hüttelmaier, T., Käser, B., Akkermann, J., Weiler, S. (2019). Mehrdimensionale Risiken und Gefährdungen durch Instandsetzungsstau bei Verkehrsinfrastrukturen. *Bevölkerungsschutz*(4), 28–33.

IHK Darmstadt Rhein Main Neckar (Ed.). (2017). *Logistikstudie.* Retrieved 03.05.2022, from `https://www.researchgate.net/publication/332633175_Logistikstudie_der_IHK_Darmstadt_Rhein_Main_Neckar`

Ivanov, D., Dolgui, A. (2019). Low-Certainty-Need (LCN) Supply Chains: A New Perspective in Managing Disruption Risks and Resilience. *International Journal of Production Research*, *57*(15-16), 5119–5136.

Jiao, H., Li, W., Ma, D. (2022). Assessment of Life Loss Due to Dam Breach using Improved Variable Fuzzy Method. *Scientific reports*, *12*(1), 3237.

Joeris, H.-J. (2016). *Instandhaltung von Wasserbauwerken - Kernaufgabe der WSV*. Karlsruhe. Retrieved 06.05.2022, from `http://docplayer.org/77002463-Instandhaltung-von-wasserbauwerken-kernaufgabe-der-wsv.html`

Jonkman, S. N., Bočkarjova, M., Kok, M., Bernardini, P. (2008). Integrated Hydrodynamic and Economic Modelling of Flood Damage in the Netherlands. *Ecological Economics*, *66*(1), 77–90.

Jüpner, R., Bachmann, D., Fekete, A., Hartmann, T., Pohl, R., Schmitt, T., Schulte, A. (2018). Resilienz im Hochwasserrisikomanagement. *KW - Korrespondenz Wasserwirtschaft*(11), 656–663.

Jüttner, U., Peck, H., Christopher, M. (2003). Supply Chain Risk Management: Outlining an Agenda for Future Research. *International Journal of Logistics Research and Applications*, *6*(4), 197–210.

Käki, A., Salo, A., Talluri, S. (2015). Disruptions in Supply Networks: A Probabilistic Risk Assessment Approach. *Journal of Business Logistics*, *36*(3), 273–287.

Kamalahmadi, M., Parast, M. M. (2016). A review of the literature on the principles of enterprise and supply chain resilience: Major findings and directions for future research. *International Journal of Production Economics*, *171*, 116–133.

Kaplan, S., Garrick, B. J. (1981). On The Quantitative Definition of Risk. *Risk Analysis*, *1*(1), 11–27.

Katina, P. F., Hester, P. T. (2013). Systemic Determination of Infrastructure Criticality. *International Journal of Critical Infrastructures*, *9*(3), 211.

Katina, P. F., Keating, C. B. (2015). Critical Infrastructures: A Perspective from Systems of Systems. *International Journal of Critical Infrastructures*, *11*(4), 316.

Ke, G. Y., Verma, M. (2021). A Framework to Managing Disruption Risk in Rail-Truck Intermodal Transportation Networks. *Transportation Research Part E: Logistics and Transportation Review*, *153*, 102340.

Kelly, S. (2015). Estimating Economic Loss from Cascading Infrastructure Failure: A Perspective on Modelling Interdependency. *Infrastructure Complexity*, *2*(1), 1–13.

Kies, J. (2019). Schneller bauen - gründlich planen oder zügig entscheiden. In Bundesanstalt für Wasserbau (Ed.), . Karlsruhe.

Klockow, S., Hofer, W. (1991). Improvement of Road Maintenance Practices in Developing Countries: Case Study from Nepal. *Transportation Research Part A: General*, *25*(2-3), 113–120.

Kobbacy, K., Murthy, D. (2008). *Complex System Maintenance Handbook*. London: Springer London.

Kochan, C. G., Nowicki, D. R. (2018). Supply chain resilience: a systematic literature review and typological framework. *International Journal of Physical Distribution & Logistics Management*, *48*(8), 842–865.

Kopper, C., Gawel, E., Hartwig, K. H., Rothengatter, W., Eisenkopf, A. (2013). Die Verkehrsinfrastruktur in Deutschland: Marode und unterfinanziert. *Wirtschaftsdienst*(10), 659–677.

Kostka, G., Anzinger, N. (2016). Large Infrastructure Projects in Germany: A Cross-sectoral Analysis. In G. Kostka J. Fiedler (Eds.), (pp. 15–38). Cham: Springer International Publishing.

Kotowska, I., Mańkowska, M., Pluciński, M. (2018). Inland Shipping to Serve the Hinterland: The Challenge for Seaport Authorities. *Sustainability*, *10*(10), 3468.

Kunert, U., Link, H. (2013). Transport Infrastructure: Higher Investments Needed to Preserve Assets. *DIW Economic Bulletin*, *3*(10).

Kvam, P. H., Miller, J. (2002). Common Cause Failure Prediction using Data Mapping. *Reliability Engineering & System Safety*, *76*(3), 273–278.

Lam, P. (1999). A Sectoral Review of Risks Associated with Major Infrastructure Projects. *International Journal of Project Management*, *17*(2), 77–87.

Lambiase, A., Mastrocinque, E., Miranda, S., Lambiase, A. (2013). Strategic Planning and Design of Supply Chains: A Literature Review. *International Journal of Engineering Business Management*, *5*, 49.

Langhagen-Rohrbach, C. (2007). Verkehrsinfrastruktur und Public-Private-Partnership. *Raumforschung und Raumordnung*, *65*(6), 539–545.

Laugé, A., Hernantes, J., Sarriegi, J. M. (2015). Critical Infrastructure Dependencies: A Holistic, Dynamic and Quantitative Approach. *International Journal of Critical Infrastructure Protection*, *8*, 16–23.

Lenz, S. (2009). *Vulnerabilität kritischer Infrastrukturen.*

Li, T., Rong, L. (2020). A Comprehensive Method for the Robustness Assessment of High-Speed Rail Network with Operation Data: A Case in China. *Transportation Research Part A: Policy and Practice*, *132*, 666–681.

Lim, M. K., Bassamboo, A., Chopra, S., Daskin, M. S. (2013). Facility Location Decisions with Random Disruptions and Imperfect Estimation. *Manufacturing & Service Operations Management*, *15*(2), 239–249.

Linnenluecke, M. K. (2017). Resilience in Business and Management Research: A Review of Influential Publications and a Research Agenda. *International Journal of Management Reviews*, *19*(1), 4–30.

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

Lowrance, W. W., Klerer, J. (1976). Of Acceptable Risk: Science and the Determination of Safety. *Journal of The Electrochemical Society*, *123*(11), 373C.

Lücker, F., Seifert, R. W., Biçer, I. (2019). Roles of Inventory and Reserve Capacity in Mitigating Supply Chain Disruption Risk. *International Journal of Production Research*, *57*(4), 1238–1249.

Manfredi, S., Di Tucci, E., LATORA, V. (2018). Mobility and Congestion in Dynamical Multilayer Networks with Finite Storage Capacity. *Physical Review Letters*, *120*(6), 068301.

Matsuo, H. (2015). Implications of the Tohoku Earthquake for Toyota's Coordination Mechanism: Supply Chain Disruption of Automotive Semiconductors. *International Journal of Production Economics*, *161*, 217–227.

McCalla, R. J., Slack, B., Comtois, C. (2001). Intermodal Freight Terminals: Locality and Industrial Linkages. *The Canadian Geographer/Le Géographe canadien*, *45*(3), 404–413.

Melo, M. T., Nickel, S., Saldanha-da Gama, F. (2009). Facility Location and Supply Chain Management - a Review. *European Journal of Operational Research*, *196*(2), 401–412.

Meneses, S., Ferreira, A., Collop, A. (2013). Multi-Objective Decision-Aid Tool for Pavement Management. *Proceedings of the ICE - Transport*, *166*(2), 79–94.

Meng, F., Fu, G., Farmani, R., Sweetapple, C., Butler, D. (2018). Topological Attributes of Network Resilience: A Study in Water Distribution Systems. *Water Research*, *143*, 376–386.

Ministerium für Bauen, Wohnen Stadtentwicklung und Verkehr des Landes Nordrhein-Westfalen (Ed.). (2016). *Mobilität in Nordrhein-Westfalen Daten und Fakten 2015/2016: Straßenverkehr – ÖPNV und Eisenbahn – Binnenschiffsverkehr – Luftverkehr.* Retrieved

01.12.2022, from https://broschuerenservice.nrw.de/vm/shop/Mobilit%C3%A4t_in_Nordrhein-Westfalen_Daten_und_Fakten_2015_2016

Mohammadi, M., Jula, P., Tavakkoli-Moghaddam, R. (2019). Reliable Single-Allocation Hub Location Problem with Disruptions. *Transportation Research Part E: Logistics and Transportation Review*, *123*, 90–120.

Morcous, G., Lounis, Z. (2005). Maintenance Optimization of Infrastructure Networks using Genetic Algorithms. *Automation in Construction*, *14*(1), 129–142.

Moss, T. (2011). *Planung technischer Infrastruktur für die Raumentwicklung: Ansprüche und Herausforderungen in Deutschland* (Vol. Bd. 235). Hannover.

Muir-Wood, R. (2015). what does a business need to know about the likely impacts of climate change? *Risk Management Solutions*.

Novotný, P., Markuci, J., Titko, M., Slivková, S., Ŕehák, D. (2015). Practical Application Of A Model For Assessing The Criticality Of Railway Infrastructure Elements. *TRANSACTIONS of the VŠB – Technical University of Ostrava, Safety Engineering Series*, *10*(2), 26–32.

Ocampo, L., Masbad, J. G., Noel, V. M., Omega, R. S. (2016). Supply-Side Inoperability Input-Output Model (SIIM) for Risk Analysis in Manufacturing Systems. *Journal of Manufacturing Systems*, *41*, 76–85.

OECD. (2020). *Financing Water Supply, Sanitation and Flood Protection*.

Ouyang, M. (2014). Review on Modeling and Simulation of Interdependent Critical Infrastructure Systems. *Reliability Engineering & System Safety*, *121*, 43–60.

Oztanriseven, F., Nachtmann, H. (2020). Modeling Dynamic Behavior of Navigable Inland Waterways. *Maritime Economics & Logistics*, *22*(2), 173–195.

Panayiotou, C. G., Ellinas, G., Kyriakides, E., Polycarpou, M. (Eds.). (2016). *Critical information infrastructures security: 9th international conference, critis 2014, limassol, cyprus, october 13-15, 2014, revised selected papers* (Vol. 8985). Cham: Springer.

Park, Y., Hong, P., Roh, J. J. (2013). Supply Chain Lessons from the Catastrophic Natural Disaster in Japan. *Business Horizons*, *56*(1), 75–85.

Pérez-Rosés, H. (2018). Sixty Years of Network Reliability. *Mathematics in Computer Science*, *12*(3), 275–293.

Puls, T. (2013). *Stur in den Stau? Ein Plädoyer für neue Wege in der deutschen Verkehrspolitik* (Vol. 59). Köln: Inst. der Dt. Wirtschaft.

Radmilovic, Z., Maras, V. (2011). Role of Danube Inland Navigation in Europe. *International Journal for Traffic and Transport Engineering*, *1*(1).

Reed, M. S., Graves, A., Dandy, N., Posthumus, H., Hubacek, K., Morris, J., ... Stringer, L. C. (2009). Who's in and Why? A Typology of Stakeholder Analysis Methods for Natural Resource Management. *Journal of environmental management*, *90*(5), 1933–1949.

Rezaei, J., van Roekel, W. S., Tavasszy, L. (2018). Measuring the Relative Importance of the Logistics Performance Index Indicators using Best Worst Method. *Transport Policy*, *68*, 158–169.

Rietveld, P. (1994). Spatial Economic Impacts of Transport Infrastructure Supply. *Transportation Research Part A: Policy and Practice*, *28*(4), 329–341.

Rinaldi, S. M., Peerenboom, J., Kelly, T. K. (2001). Identifying, Understanding, and Analyzing Critical Infrastructure Interdependencies. *IEEE Control Systems*, *21*(6), 11–25.

Rohács, J., Simongáti, G. (2007). The Role of Inland Waterway Navigation in a Sustainable Transport System. *Transport*, *22*(3), 148–153.

Rose, A. (2004). Economic Principles, Issues, and Research Priorities in Hazard Loss Estimation. In (pp. 13–36). Springer, Berlin, Heidelberg.

Rothengatter, W. (2000). Evaluation of Infrastructure Investments in Germany. *Transport Policy*, *7*(1).

Santos, J. R., Haimes, Y. Y. (2004). Modeling the Demand Reduction Input-Output (I-O) Inoperability due to Terrorism of Interconnected Infrastructures. *Risk analysis : an official publication of the Society for Risk Analysis*, *24*(6), 1437–1451.

Sawik, T. (2019). Disruption Mitigation and Recovery in Supply Chains Using Portfolio Approach. *Omega*, *84*, 232–248.

Schmidt-Bäumler, H. (2020). *Multikriterielle Entscheidungsunterstützung in der risiko-basierten Instandhaltungsplanung am Beispiel der Verkehrswasserbauwerke.* Karlsruhe.

Scholten, A., Rothstein, B. (2012). *Auswirkungen von Niedrigwasser und Klimawandel auf die verladende Wirtschaft, Binnenschifffahrt und Häfen entlang des Rheins: Untersuchungen zur gegenwärtigen und zukünftigen Vulnerabilität durch Niedrigwasser*. Würzburg : Selbstverl. des Inst. für Geographie und Geologie der Julius-Maximilians-Univ.

Scott, D. M., Novak, D. C., Aultman-Hall, L., Guo, F. (2006). Network Robustness Index: A new Method for Identifying Critical Links and Evaluating the Performance of Transportation Networks. *Journal of Transport Geography*, *14*(3), 215–227.

Shadabfar, M., Mahsuli, M., Zhang, Y., Xue, Y., Ayyub, B. M., Huang, H., Medina, R. A. (2022). Resilience-based design of infrastructure: Review of models, methodologies, and computational tools. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*, *8*(1), 03121004.

Shin, S., Lee, S., Judi, D., Parvania, M., Goharian, E., McPherson, T., Burian, S. (2018). A Systematic Review of Quantitative Resilience Measures for Water Infrastructure Systems. *Water*, *10*(2), 164.

Short, J., Kopp, A. (2005). Transport infrastructure: Investment and planning. policy and research aspects. *Transport Policy*, *12*(4), 360–367.

Shrivastava, S., Sonpar, K., Pazzaglia, F. (2009). Normal Accident Theory Versus High Reliability Theory: A Resolution and Call for an Open Systems View of Accidents. *Human Relations*, *62*(9), 1357–1390.

Shukla, A., Agarwal Lalit, V., Venkatasubramanian, V. (2011). Optimizing Efficiency–Robustness Trade–Offs in Supply Chain Design under Uncertainty due to Disruptions. *International Journal of Physical Distribution & Logistics Management*, *41*(6), 623–647.

Siegrist, Cvetkovich. (2000). Perception of Hazards: The Role of Social Trust and Knowledge. *Risk Analysis*, *20*(5), 713–719.

Slovic, P., Fischhoff, B., Lichtenstein, S. (1980). Facts and Fears: Understanding Perceived Risk. In (pp. 181–216). Springer, Boston, MA.

Smith, D. J. (2011). *Reliability, Maintainability, and Risk: Practical Methods for Engineers*. Amsterdam and Boston: Butterworth-Heinemann/Elsevier.

Solomon, B., Otoo, E., Boateng, A., Ato Koomson, D. (2021). Inland Waterway Transportation (IWT) in Ghana: A Case Study of Volta Lake Transport. *International Journal of Transportation Science and Technology*, *10*(1), 20–33.

Spegel, E. (2017). Valuing the Reduction of Floods: Public Officials' versus Citizens' Preferences. *Climate Risk Management*, *18*, 1–14.

Starr, C. (1969). Social Benefit Versus Technological Risk. *Science*, *165*(3899), 1232–1238.

Stewart, M. G., Wang, X., Nguyen, M. N. (2011). Climate Change Impact and Risks of Concrete Infrastructure Deterioration. *Engineering Structures*, *33*(4), 1326–1337.

Stuchtey, R. (2010). Finanzierung der Seehafeninfrastruktur im Föderalismus. In H.-D. Haasis, H. Kramer, B. Lemper (Eds.), . Frankfurt am Main and Berlin and Bern and Wien: Lang.

Sullivan, J. L., Novak, D. C., Aultman-Hall, L., Scott, D. M. (2010). Identifying Critical Road Segments and Measuring System-Wide Robustness in Transportation Networks with Isolating Links: A Link-Based Capacity-Reduction Approach. *Transportation Research Part A: Policy and Practice*, *44*(5), 323–336.

Syan, C. S., Ramsoobag, G. (2019). Maintenance Applications of Multi-Criteria Optimization: A Review. *Reliability Engineering & System Safety*, *190*, 106520.

Taghizadeh, H., Hafezi, E. (2012). The Investigation of Supply Chain's Reliability Measure: A Case Study. *Journal of Industrial Engineering International*, *8*(1), 1–10.

Taylor, M. A. P., D'este, G. M. (Eds.). (2003). *Concepts of Network Vulnerability and Applications to the Identification of Critical Elements of Transport Infrastructure.* New Zealand Transport Research Forum Wellington, New Zealand.

Temursho, U. (2016). *Backward and Forward Linkages and Key Sectors in the Kazakhstan Economy: Services sector in Kazahstan as an Engine for Diversified Economic Growth - Final Report*. Retrieved 26.01.2022, from `https://www.adb.org/projects/documents/kaz-47110-001-dpta-2`

Theoharidou, M., Kotzanikolaou, P., Gritzalis, D. (2009). Risk-Based Criticality Analysis. In C. Palmer S. Shenoi (Eds.), *Critical Infrastructure Protection III* (pp. 35–49). Berlin, Heidelberg: Springer Berlin Heidelberg.

Theoharidou, M., Kotzanikolaou, P., Gritzalis, D. (2010). A Multi-Layer Criticality Assessment Methodology Based on Interdependencies. *Computers & Security*, *29*(6), 643–658.

Timmermans, D., Oudhoff, J. (2011). *Different Formats for the Communication of Risks: Verbal, Numerical, and Graphical Formats*. American Cancer Society.

Tomlin, B. (2006). On the Value of Mitigation and Contingency Strategies for Managing Supply Chain Disruption Risks. *Management Science*, *52*(5), 639–657.

Tonn, G., Reilly, A., Czajkowski, J., Ghaedi, H., Kunreuther, H. (2021). U.S. Transportation Infrastructure Resilience: Influences of Insurance, Incentives, and Public Assistance. *Transport Policy*, *100*(4), 108–119.

Topics Geo Natural Catastrophes 2016. (2017). Retrieved 03.09.2019, from `https://www.munichre.com/touch/naturalhazards/de/publications/topics-geo/2016/index.html`

Trechow, P. (2011). Verkehr auf Wasserstraßen lässt sich nicht herbeibauen: Ausbau von Wasserstraßen: Interview. *ingenieur.de*, *2011*.

Uddin, M., Huynh, N. (2019). Reliable Routing of Road-Rail Intermodal Freight under Uncertainty. *Networks and Spatial Economics*, *19*(3), 929–952.

Ukkusuri, S. V., Yushimito, W. F. (2009). A Methodology to Assess the Criticality of Highway Transportation Networks. *Journal of Transportation Security*, *2*(1), 29–46.

UN/ISDR (Ed.). (2002). *Glossary.* Retrieved 13.11.2019, from `https://www.unisdr.org/2003/campaign/english/5_Glossary_eng.pdf`

Utne, I. B., Hokstad, P., Vatn, J. (2011). A Method for Risk Modeling of Interdependencies in Critical Infrastructures. *Reliability Engineering & System Safety*, *96*(6), 671–678.

van Bussel, G., Zaayer, M. B. (2001). Reliability, Availability and Maintenance Aspects of Large-Scale Offshore Wind Farms, a Concepts Study. In C. French (Ed.), *Marec 2001.* London: Institute of Marine Engineers.

Vaurio, J. K. (2005). Uncertainties and Quantification of Common Cause Failure Rates and Probabilities for System Analyses. *Reliability Engineering & System Safety*, *90*(2), 186–195.

Vrijling, J. K., van Gelder, P. A., Ouwerkerk, S. J. (2006). Criteria for Acceptable Risk in the Netherlands. *0784408157*(UR - https://trid.trb.org/view/842174).

Wagner, S. M., Neshat, N. (2010). Assessing the Vulnerability of Supply Chains using Graph Theory. *International Journal of Production Economics*, *126*(1), 121–129.

Wehrle, R., Wiens, M., Schultmann, F., Akkermann, J., Bödefeld, J. (2020). Ebenensystem zur Resilienzbewertung kritischer Verkehrsinfrastrukturen am Beispiel der Wasserstraßen. *Bautechnik*, *97*(6), 395–403.

Wesolowsky, G. O., Truscott, W. G. (1975). The Multiperiod Location-Allocation Problem with Relocation of Facilities. *Management Science*, *22*(1), 57–65.

Willson, R., United States. Bureau of Transportation Statistics. (1998). *Impacts and Responses : Goods movement after the Northridge Earthquake*. Not Available.

World Economic Forum. (2017). *Shaping the Future of Production: Four Contrasting Perspectives in 2030.* Cologny/Geneva.

Wouters, M., Anderson, J. C., Wynstra, F. (2005). The Adoption of Total Cost of Ownership for Sourcing Decisions—-A Structural Equations Analysis. *Accounting, Organizations and Society*, *30*(2), 167–191.

WSV. (2022). *Elwis-database.* Retrieved 17.05.2022, from `http://www.elwis.de`

Yamada, T., Febri, Z. (2015). Freight Transport Network Design Using Particle Swarm Optimisation in Supply Chain - Transport Supernetwork Equilibrium. *Transportation Research Part E: Logistics and Transportation Review*, *75*, 164–187.

Zarghami, S. A., Gunawan, I., Schultmann, F. (2019). Exact Reliability Evaluation of Infrastructure Networks using Graph Theory. *Quality and Reliability Engineering International*, *12*(4), 369.

Zhang, P., Peeta, S. (2011). A Generalized Modeling Framework to Analyze Interdependencies among Infrastructure Systems. *Transportation Research Part B: Methodological*, *45*(3), 553–579.

Zio, E. (2016). Challenges in the Vulnerability and Risk Analysis of Critical Infrastructures. *Reliability Engineering & System Safety*, *152*, 137–150.

Journal article

Wehrle, R., Gast, J., Wiens, M., Schultmann, F. (2022). On the Influence of Infrastructure Availability on Companies Decisions towards Modal Shift and Relocation of Facilities. *Submitted to a scientific journal*.

Wehrle, R., Wiens, M., Neff, F., Schultmann, F. (2022). Economic risk potential of infrastructure failure considering inland waterways. *Submitted to a scientific journal*.

Wehrle, R., Wiens, M., Schultmann, F. (2021). Application of Collaborative Serious Gaming for the Elicitation of Expert Knowledge and towards creating Situation Awareness in the Field of Infrastructure Resilience. *International Journal of Disaster Risk Reduction*.

Wehrle, R., Wiens, M., Schultmann, F. (2022a). Evaluation of the Potential of Infrastructure Funds using the Case of Inland Waterways. *Submitted to a scientific journal*.

Wehrle, R., Wiens, M., Schultmann, F. (2022b). Measuring Systemic and Cascading Risk of Transport Infrastructure based on a Systemic Approach and Input-Output Modelling using the Example of Waterways. *Submitted to a scientific journal*.

Wehrle, R., Wiens, M., Schultmann, F., Akkermann, J., Bödefeld, J. (2020). Ebenensystem zur Resilienzbewertung kritischer Verkehrsinfrastrukturen am Beispiel der Wasserstraßen. *Bautechnik*, *97*(6), 395–403.

Conference proceedings

Gast, J., Wehrle, R. (2019). Application of the Concept of Supply Chain Reliability for an Availability Assessment of Inland Waterway Systems. In *Cambridge International Manufacturing Symposium.* Apollo - University of Cambridge Repository.

Gast, J., Wehrle, R., Wiens, M., Schultmann, F. (2020). Impact of Notification Time on Risk Mitigation in Inland Waterway Transport. In *Hamburg International Conference of Logistics (HICL).* Hamburg: TUHH Universitätsbibliothek.

Part II

Companion Articles

Overview of Related Publications

Study A

Gast, J., Wehrle, R. (2019). Application of the Concept of Supply Chain Reliability for an Availability Assessment of Inland Waterway Systems. Apollo - University of Cambridge Repository. doi: 10.17863/CAM.45875

Study B

Gast, J., Wehrle, R., Wiens, M., Schultmann, F. (2020). Impact of Notification Time on Risk Mitigation in Inland Waterway Transport. In *Hamburg International Conference of Logistics (HICL)*. Hamburg: TUHH Universitätsbibliothek. doi: 10.15480/882.3115

Study C

Wehrle, R., Wiens, M., Neff, F., Schultmann, F. (2022). Economic risk potential of infrastructure failure considering inland waterways. *Submitted to a scientific journal*.

Study D

Wehrle, R., Gast, J., Wiens, M., Schultmann, F. (2022). On the Influence of Infrastructure Availability on Companies Decisions towards Modal Shift and Relocation of Facilities. *Submitted to a scientific journal*.

Study E

Wehrle, R., Wiens, M., Schultmann, F. (2021). Application of Collaborative Serious Gaming for the Elicitation of Expert Knowledge and towards creating Situation Awareness in the Field of Infrastructure Resilience. *International Journal of Disaster Risk Reduction*, 102–665. doi: 10.1016/j.ijdrr.2021.102665

Study F

Wehrle, R., Wiens, M., Schultmann, F. (2022). Measuring Systemic and Cascading Risk of Transport Infrastructure based on a Systemic Approach and Input-Output Modelling using the Example of Waterways. *Submitted to a scientific journal*.

Study G

Wehrle, R., Wiens, M., Schultmann, F. (2022). Evaluation of the Potential of Infrastructure Funds using the Case of Inland Waterways. *Submitted to a scientific journal*.

A Application of the concept of supply chain reliability for an availability assessment of inland waterway systems

Abstract[1]

The concept of Supply Chain Reliability has received some attention in recent years due to disruptions that affect Supply Chains and endanger business continuity. This paper examines the current state of the literature on Supply Chain Reliability. The literature's underlying concept of Reliability Theory is applied to assess the availability of a restrictive infrastructure network based on empirical failure data in a case study about the West-German canal system. Furthermore, the availability of transport flows inside the system is calculated. The model analyses the state of the canal system regarding transportation flows by calculating its component availability. The model is generalisable for inland waterways and results in a quantitative indicator for the risk assessment of Supply Chain Disruptions and Supply Chain Resilience. This indicator, the reliability value, can be integrated into the Supply Chain Risk Management of affected organisations and used as a parameter of procurement models.

Keywords: Supply Chain Reliability; Infrastructure Availability; Supply Chain Disruption; Reliability Theory; Inland Waterway Transportation

A.1 Introduction

Supply Chains (SC) face growing threats of disruptions due to external events such as disasters, conflicts, market volatility, and policy-making. The organisations of the SCs need to recognise what needs to be done to assure production in certain levels and to estimate the maximum tolerable recovery period after a disruption occurs (Faertes, 2015). Global sourcing and global selling, as well as lean management practices, have exacerbated the threat of disruption even further by increasing

[1] This chapter includes the preprint of the article "Application of the concept of supply chain reliability for an availability assessment of inland waterway systems" by Johannes Gast, Frank Schultmann, and myself (Gast and Wehrle, 2019).

SC Vulnerability (Christopher, 2016). As a result, disruptive events can have severe business consequences. These consequences are not limited to one companionany but companionanies further downstream of the disrupted SC, too (Merz et al., 2009).

Access to inland waterways allows industries like chemical industrial parks or power plants to procure high volumes of low-cost chemicals and materials as well as the logistics handling of some dangerous goods and large machinery. However, a SC dependent on waterway infrastructure becomes subject to the functionality and availability of the infrastructure, which is not always given, i.e. in case of extreme weather effects: BASF SE wrote off more than EUR 200 million because of supply disruptions directly related to the historic 2018 low-tides of the river Rhine (BASF SE, 2019). Marl and other ports were not accessible for almost two weeks in February 2012 due to ice-coverage of the canal “Datteln-Hamm-Kanal” (WSV, 2022). SC disruptions in chemical industrial parks have notable impacts for many downstream industries because one finds their products nearly everywhere. Because a disruption at the chemical industry park located in Marl caused a shortage of a necessary component for the global automotive industry in 2012, the site was identified as a nexus supplier hidden in various multi-tier SCs (Yan et al., 2015). The examples above highlight the dependency of certain SCs on the availability of inland waterways.

Anticipating and mitigating the impact of disruptive events is part of SC Risk Management. Next to the likelihood of a risk event, the event duration and SC capabilities to cope with the event, i.e. by modal shift or safety stocks, need to be considered as part of SC Risk Management, too. The assessment of SC Reliability is capable of applying quantitative methods from Reliability Theory that capture the configuration of the network, the current state of the network, and time dynamics, thereby addressing the shortcomings of qualitative SC Risk Management models (Gast, 2019). In order to contribute to the field of Supply Chain Reliability and to obtain a quantitative indicator of the risk associated with inland waterway transport, this paper presents a case study on the availability of the West-German canal system by:

- assessing the availability of inland waterway infrastructure in a case study about the West-German canal system.

The case study was chosen due to the following reasons: on the one hand, this system handles the second most goods volume transported on inland waterways in Germany, after the river Rhine, and acts as a connection to other German canals. On the other hand, ships have to pass multiple locks which are occasionally undergoing unscheduled maintenance, thereby reducing the availability of the system.

The paper is divided into five sections: First, this paper summarises published literature on SC Reliability and presents existing concepts, models and applications. In the following section, the paper develops the methodology by using appropriate methods from Reliability Theory. Then, the developed methodology is applied to assess the availability of the West-German canal system. Afterwards, the paper presents and discusses the obtained results. Last, the paper puts the results into the perspective of SCs that depend on the availability of infrastructure and sketches further research steps.

A.2 Literature Review

The following section provides an overview of previous attempts to quantify SC Reliability. As one of the first, journal-published, research contributions in that field, Klimov and Merkuryev (2008) apply the Reliability Structure Function from Reliability Theory in the context of SC Risk Management. Miman and Pohl (2008) argue that mission fulfilment has priority for SCs, which encounter unforeseen events, and thus costs should be considered secondarily; the authors propose a model of Network Reliability in a real-world logistics system to ensure that supply always meets demand in case of SC Disruptions. Moreover, the authors consider higher cost levels and costs of inventory holding to ensure that the routing, in case of multiple options, prefers more reliable node connections. However, the inland waterway routes, as well as capacities for modal shifts, are limited. Hence, infrastructure networks require resilience with emphasis on the recovery period (Hosseini and Barker, 2016).

Ohmori and Yoshimoto (2013) suggest that risk can be seen as the counterpart of reliability and propose the concept of Network Reliability as a tool in order to address the shortcomings of SC risk management. Furthermore, considering the features of network reliability, resilience got introduced into the context of SC Reliability, answering the question, "whether SC processes can be recovered by the specified target time" Ohmori and Yoshimoto (2013) — resembling the aspect of maintainability in Reliability Theory. Finally, Ha et al. (2018) structurally derive a definition of SC Reliability. The authors point out in their conducted literature review that the literature on SC Reliability is scarce and does not contain a definition so far that captures time, network configuration, and capacity throughput. On that account, they translatethe mathematical definition of reliability of an arbitrary component system into the terminology of SC.

The literature covers both the dimension of disruptions (contingency logistics) and the logistic process dimension of delivery reliability (service levels). For most parts, the literature provides concepts that are not applied in real-world logistics systems (Gast, 2019; Ha et al., 2018). However, the literature on SC Reliability has not yet provided an attempt to calculate the availability of a SC system with consideration of recovery time (~resilience) from empirical data. Furthermore, SC literature points out three main limitations to the application of SC Reliability next to the lack of applications in case studies (Gast, 2019):

- difficulties in defining system boundaries in which to calculate reliability values.
- the availability of failure data in order to derive reliability parameters.
- the complexity of a network with n nodes poses computational limitations, as enumeration and decomposition algorithms with exponential runtime $(\mathrm{O}(2^{\mathrm{n}}))$ have to be applied.

The main limitations of applying SC Reliability, are not present in assessing the infrastructure availability of the West-German canal system, because: First, the system in scope consists of four canals and 14 locks; thus, computational limitations do not apply. Second, the waterway infrastructure and canal entry and exit points are well-defined system boundaries. Third, historical data about the failure of infrastructure objects are available.

The next section presents the methodology that is used to analyse the SC Reliability of SCs, which cargo flows move through the West-German canal system.

A.3 Methodology

The methodology of this paper uses and presents basic models from Reliability Theory, which the literature of SC Reliability mostly considers, too. Reliability Theory is well-studied in the past decades and mainly applied in construction and manufacturing (cf. Ebeling, 2017). Then, the model is applied to the West-German canal system and used to quantify the availability of the inland waterway structure.

A.3.1 Context from Reliability Theory

"Reliability is defined to be the probability that a component or system will perform a required function for a given period when used under stated operating conditions" (Ebeling, 2017). Time is not inherent to SC Risk Management; though, time is an inherent attribute of reliability. Both statements are expressed in Exp. A.1:

$$R(t) = Pr\{t \leq T\} = e^{-\lambda(t)} \qquad \text{(Exp. A.1)}$$

where R(t) is the reliability level expressed as the probability $\mathrm{Pr}\{\mathrm{T} \geq \mathrm{t}\}$ that the system is in a nonfailure state at time t, in a given period T, and λ(t) is the HRF that influences failure likelihood and the distribution of failures. The HRF can be obtained from empirical data and their distribution or with scientific knowledge about the failure modes. Another essential equation is the Mean Time To Failure (MTTF) defined in Exp. A.2. The MTTF returns the expected point of time in which a failure occurs with a likelihood of 50%.

$$MTTF = \int_0^\infty R(t)\, dt \qquad \text{(Exp. A.2)}$$

Analogously to Exp. A.2, Exp. A.3 defines the Mean Time To Repair (MTTR):

$$MTTR = \int_0^\infty M(t)\, dt \qquad \text{(Exp. A.3)}$$

where M(t) is the Repair Function, which describes the behaviour of an offline component. MMTR is the probability that the repair of a component is performed in a given period. The following relationship given by Exp. A.4 applies for the HRF mentioned above:

$$HRF = -ln\big[(MTBF - MTTR)'\big] \qquad \text{(Exp. A.4)}$$

Ebeling (2017) defines Availability as the probability that a component or system is performing its required function at a given point in time when used under stated operating conditions. Exp. A.5 expresses the Availability of a component using MTBF and MTTR defined above:

$$A = \frac{MTBF}{MTBF + MTTR} \tag{Exp. A.5}$$

Availability can be described in qualitative terms or quantitative terms as a probability, depending on whether MTBF and MTTR only contain the expected value for a period T or also information about the failure distribution.

The distribution of failure likelihoods can vary significantly depending on the failure mode in focus, system properties, environmental parameters and loads (Ebeling, 2017). If not enough information about the distribution is available, the principle of maximum entropy applies, meaning that the normal distribution can be assumed, because its application requires the least information (Pinto et al., 2013). From the Reliability Function of a component, the Reliability Structure Function can be obtained to calculate the reliability value of a system. Systems are sets of elements that stand in a mutual relationship with each other. A component of a system can also be a system, in that case, referred to as a subsystem. In the following, the Structure Function is described, which finds application in almost all SC Reliability models to this date. The function allows expressing complex systems with only one parameter: their reliability. The Structure Function assumes that there are only two states for a component xi as described in Exp. A.6:

$$x_i = \begin{cases} 1 & \text{if the i}^{\text{th}} \text{ component works} \\ 0 & \text{if the i}^{\text{th}} \text{ component fails} \end{cases} \tag{Exp. A.6}$$

$$\phi(x) = \phi(x_1, x_2, \cdots, x_n) \tag{Exp. A.7}$$

The Reliability Structure Function $\phi(\mathrm{x})$ of a system with n-components, as defined in Exp. A.7, incorporates Exp. A.6 and assesses whether the whole system is in a working or failing state. The assessment result depends on the relationship of the components; e.g., if the two components in a two-component system are in series, system reliability is calculated by the product of their Reliability Function, and if the first component fails, the system fails. If set in parallel, both components have to fail in order for the system to fail because redundancy exists. If knowledge about the offline time is available through the MTTR, the information about the configuration in the Reliability Structure Function can be used to assess the availability of a path through the system (Ebeling, 2017).

The following section outlines the scope of the availability assessment using the presented context.

A.3.2 Availability assessment of an infrastructure network in a case study

The German waterway authority pronounces timestamped, binding notifications regarding the German inland waterways (“Nachrichten für die Binnenschifffahrt”). The notifications are archived and accessible online (cf. Ebeling, 2017). For this analysis, 2,199 observations containing information about restrictions, closures, and their respective durations were collected from the database and syntactically edited. In a second step, observations regarding infrastructure objects that are not related to the canals’ locks or the waterway of the canals were dropped because their impact on the availability of the canal system could not be fully determined. Third, suspended notices were excluded, too. The filtered dataset now contains 1,088 observations of closures of waterways and locks in the West-German canal system since 2006.

Figure A.1 outlines the network configuration of the West-German canal system with its canals “Wesel-Datteln-Kanal” (WDK), “Dortmund-Ems-Kanal” (DEK), “Rhein-Herne-Kanal” (RHK), and “Datteln-Hamm-Kanal” (DHK). The canal locks mainly possess two lock chambers (The network configuration in this paper considers the lock “Ruhrschleuse Duisburg” as the second chamber of the lock “Duisburg Meiderich”).

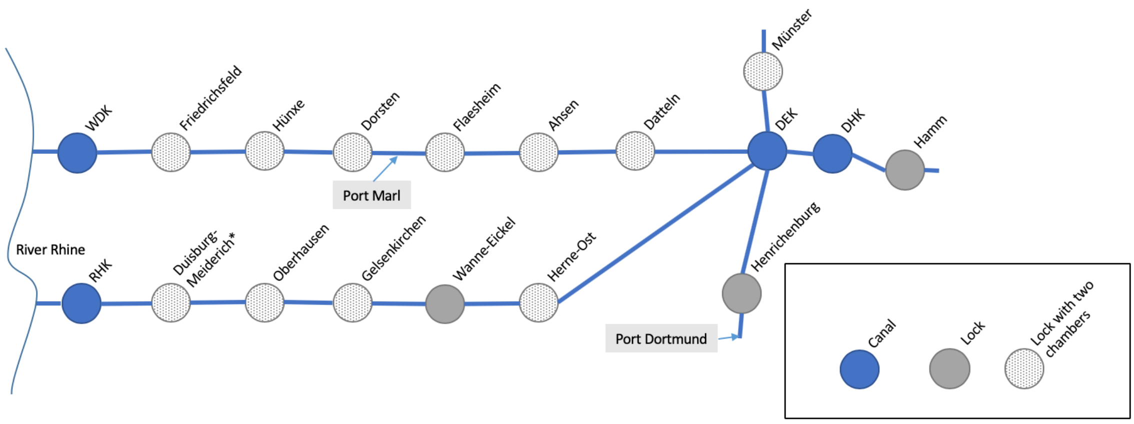

Figure A.1: Network of the West-German canal system

The canal system would not be available if all locks of a single two-chamber lock or the waterway are closed.

A.4 Results

Table A.1 below presents the calculated summary of reliability parameters for each object, which are associated with an id and the number n of available observations. The MTTR and MTBF are given next to their respective Standard Deviations $\sigma(\bullet)$, and are formatted in days [d]. Two-chamber locks are assumed to be a two-component system that is set in parallel and has an independent failure distribution.

Id	Object	n	MTBF	σ(MTBF)	MTTR	σ(MTTR)	Availability
1	DEK	174	25.54	32.09	2.39	10.36	0.9144
2	DHK	46	97.64	115.87	3.07	10.64	0.9695
3	RHK	182	24.70	28.53	0.78	2.05	0.9694
4	WDK	65	66.55	75.88	0.69	0.83	0.9897
5	Ahsen	46	88.90	198.90	14.08	63.72	0.9813
6	Datteln	51	82.76	218.23	3.24	7.16	0.9986
7	Dorsten	49	85.07	195.93	8.98	41.50	0.9909
8	D.-Meiderich	54	68.20	86.41	14.05	85.92	0.9408
9	Flaesheim	40	101.10	134.44	4.88	13.32	0.9979
10	Friedrichsfeld	96	45.58	63.01	3.64	11.49	0.9945
11	Gelsenkirchen	38	120.59	183.92	5.50	9.85	0.9981
12	Hamm*	21	184.80	245.44	4.62	4.14	0.9756
13	Henrichenburg*	41	107.47	169.98	3.27	8.86	0.9705
14	Herne-Ost	22	172.82	245.13	13.32	44.65	0.9949
15	Hünxe	63	67.37	134.70	5.59	14.73	0,9941
16	Münster	6	711.80	1,025.73	8.06	7.55	0,9999
17	Oberhausen	51	72.44	202.41	20.15	68.90	0,9526
18	Wanne-Eickel*	43	103.50	136,55	2.60	7.68	0,9755

* one-chamber locks

Table A.1: Calculation of reliability parameters for the West-German canal system

Table A.1 shows the results of the calculation of reliability parameters for each object. Now, the Reliability Structure Function for a route through this component system can be derived. The following Structure Function in Exp. A.8 represents the system availability that transportation from the river Rhine (R) can access the port of Dortmund through the lock "Henrichenburg" (H).

$$\begin{aligned} A_{R\to H} &= 0.8774 \\ &= R_1 \cdot R_{13} \cdot \Big((1 - R_{WDK} \cdot R_{WDK\_locks}) \cdot (1 - R_{RHK} \cdot R_{RHK\_locks})\Big) \end{aligned} \quad \text{(Exp. A.8)}$$

where R_{DHK_locks}, R_{RHK_locks} are the respective products of the canal locks' Reliability Functions. Exp. A.1 states that the availability for a given period is expected to be 87.74%.

A.5 Discussion

The calculated Reliability Functions are based on empirical data but were subject to assumptions. The Kolmogorov-Smirnova coefficient does not validate the assumption that the failure events follow a normal distribution for two-third of the objects, thus – in the context of a reliability assessment - the principle of maximum entropy needs to be applied. The Standard Deviation is rather high as a result of outliers due to disruptive events, i.e. an accident damaging one chamber-gate at the lock “Duisburg- Meiderich” resulting in a downtime phase of 632 days. The availability of the DEK is low not only because of major disruptive events like the collapse of a canal bridge at the DEK but also due to events like rowing regattas. For the latter, notifications are given far in advance to allow affected organisations to adapt. Further works would be able to elaborate on the failure distribution with means of Reliability Theory: i.e. the distribution of failures due to nature is dependent on the current weather and season.

This paper aimed to assess the navigability of the West-German canal way and did not further examine the varying impacts of failure states: for example, the closure of the large-chamber of a lock could result up-to hours of waiting time for cargo vessels and the largest vessel classes would not be able to enter the canal anymore. In general, the model did not consider different states of the system, i.e. the reduced reliability if access to a specific lock-chamber is already restricted. Multi-state models from Network Reliability analysis may be consulted to calculate the Reliability Function; those models are also capable of capturing risk dependencies (cf. Pérez-Rosés, 2018).

Nonetheless, this paper derives a quantitative indicator that not only captures risk likelihoods throughout a network but also assesses the resilience of the considered system. This paper’s methodology obtained required reliability parameters from empirical data and assessed the infrastructure availability of the West-German canal system. SC organisations can integrate the results to optimise their procurement strategies, namely the trade-off between supplier reliability and inventory holding costs and risk mitigation strategies. Moreover, investments into reliability enhancement (risk mitigations) can be prioritised based on their expected effect on the infrastructure availability depending on the network configuration and given time scope.

A.6 Conclusion

This paper shows the feasibility of applying methods from Reliability Theory and SC Reliability to derive a quantitative indicator using publicly available data. The methodology is capable of capturing network and time dynamics that can be used in the SC risk assessment and allow companionanies to prepare mitigation strategies like adjusting stock-levels or reserving additional capacities in different modes of transport in accordance to a quantitative measure. The model can be generalised for the whole European inland waterway network. Further models from Reliability Theory and SC Reliability can extend the assessment by adding environmental parameters, which statistical methods fit into the HRF which then alters the system availability depending on the underlying distribution for period in scope (cf. Ebeling, 2017).

Acknowledgements

The authors want to thank the partners in the joint research project PREVIEW, coordinated by Dr Wiens (IIP, Karlsruhe Institute of Technology). The project is funded by the security research fund

of transportation infrastructure (SIFO) of the German Federal Ministry of Education and Research (BMBF).

References

BASF SE. (2019). *BASF Report 2018.* Retrieved 04.08.2019, from `http://www.basf.com/cz/documents/BASF_Report_2018.pdf`

Christopher, M. (2016). *Logistics & Supply Chain Management* (5th ed.). Harlow, United Kingdom: Pearson Education.

Ebeling, C. E. (2017). *An Introduction to Reliability and Maintainability Engineering* (21st ed.). New York, USA: McGraw-Hill.

ELWIS-database. (2019). Retrieved 17.05.2019, from `http://www.elwis.de`

Faertes, D. (2015). Reliability of Supply Chains and Business Continuity Management. *Procedia Computer Science*, *55*, 1400–1409.

Gast, J. (2019). *Supply Chain Reliability Management: Master Thesis.*

Gast, J., Wehrle, R. (2019). Application of the Concept of Supply Chain Reliability for an Availability Assessment of Inland Waterway Systems.

Ha, C., Jun, H.-B., Ok, C. (2018). A Mathematical Definition and Basic Structures for Supply Chain Reliability: A Procurement Capability Perspective. *Computers & Industrial Engineering*, *120*, 334–345.

Hosseini, S., Barker, K. (2016). Modeling Infrastructure Resilience using Bayesian Networks: A Case Study of Inland Waterway Ports. *Computers & Industrial Engineering*, *93*(7), 252–266.

Klimov, R., Merkuryev, Y. (2008). Simulation Model for Supply Chain Reliability Evaluation. *Ukio Technologinis ir Ekonominis Vystymas*, *14*(3), 300–311.

Merz, M., Hiete, M., Bertsch, V. (2009). Multicriteria Decision Support for Business Continuity Planning in the Event of Critical Infrastructure Disruptions. *International Journal of Critical Infrastructures*, *5*(1/2), 156.

Miman, M., Pohl, E. (2008). Modeling and Analysis of Risk and Reliability for a Contingency Logistics Supply Chain. *Journal of Risk and Reliability*, *222*, 477–494.

Ohmori, S., Yoshimoto, K. (2013). A Framework of Managing Supply Chain Disruption Risks using Network Reliability. *Industrial Engineering and Management Systems*, *12*(2), 103–111.

Pérez-Rosés, H. (2018). Sixty Years of Network Reliability. *Mathematics in Computer Science*, *12*(3), 275–293.

Pinto, R., Mettler, T., Taisch, M. (2013). Managing Supplier Delivery Reliability Risk under Limited Information: Foundations for a Human-in-the-Loop DSS. *Decision Support Systems*, *54*(2), 1076–1084.

Yan, T., Choi, T. Y., Kim, Y., Yang, Y. (2015). A Theory of the Nexus Supplier: A Critical Supplier From A Network Perspective. *Journal of Supply Chain Management*, *51*(1), 52–66.

B Impact of notification time on risk mitigation in inland waterway transport

Abstract[1]

Transport infrastructures form the backbone of today's interconnected real economy. Interruptions in the availability of these critical infrastructures occur, among other things, due to maintenance operations. Since companies and Supply Chains are dependent on planning security, an adequate notification time in advance of such interruptions is required. Otherwise, insufficient notification time limit available mitigation strategies.

First, the authors conduct a workshop concept to obtain expert knowledge from stakeholders to identify critical thresholds of notification times, which affect maintenance and logistics operations in inland waterway transport. Second, this research analyses the notification time of closures on an exemplary real-world network of inland navigation. Therefore, this paper analyses historical data about closure and notification times of inland water-ways with their particular reason for interruption.

The research reveals a high impact of notification times on logistics operations and deter-mines the planning reliability for all parties involved. Data analysis found that the notification time for the majority of the considered closures is below the identified critical threshold. As these pose threats to supply chain operations, efficient planning must address these critical thresholds.

This research is innovative as there is little analysis on inland waterways, even though there exist accessible historical data. This research contributes to this account by linking critical infrastructure, expert knowledge, and supply chain operations. Quantitative methods ex-tend the base of qualitative knowledge gained from interdisciplinary research. Stakeholders can account for notification time in their risk mitigation strategies.

[1] This chapter includes the preprint of the article "AImpact of notification time on risk mitigation in inland waterway transport" by Johannes Gast, Marcus Wiens, Frank Schultmann, and myself (Gast et al., 2020).

B.1 Introduction

Due to the Corona Pandemic, Supply Chain Risk Management (SCRM) receives significant attention in the first half of 2020. Organisations of Supply Chains (SCs) are under pressure "to recognise what needs to be done to assure production at certain levels" (Faertes, 2015). The availability of transport infrastructure is of special interest in the context of SCRM (Li et al., 2006; Hosseini et al., 2019). Within this context and besides the factors impact, probability, and resilience, another factor comes into focus: risk communication about the enaction and extent of risk mitigation measures by public authorities. In the area of risk communication between the operator and user of infrastructure, the term notification time is introduced. Notification time describes the time between the notification from the operator about an impending restriction of a transport way and the actual start of the restriction. For risks that can be identified well before their realisation, stakeholders have enough time to prepare mitigation strategies within this time. This paper introduces the aspect of notification time from the perspective of SCRM and discusses its effect on SCRM strategies.

Notification time concerning events that restrict the navigability and operational readiness of inland waterway transport is the object of study using the example of the West-German canal network. This canal network handles the second most transport volume on inland waterways in Germany following the river Rhine (cf. Federal Statistical Office of Germany, 2019). It consists of four canals: the "Wesel-Datteln-Kanal" (WDK), the "Rhein-Herne-Kanal" (RHK), the "Datteln-Hamm-Kanal" (DHK), and the "Dortmund-Ems-Kanal" (DEK). Furthermore, this paper considers two industries that meet their supply primarily through inland waterway transport and depend on the waterway navigability.

B.1.1 Motivation

Inland waterway transport is an efficient mode of transport to supply large-scale chemical parks, power stations and to transport bulk goods. It provides capabilities for the handling of certain dangerous and bulky goods (like a gas turbine with a weight of 600t). Albeit industries depend on the navigability of the waterways, which is not continuously given: the chemical company BASF SE lost over EUR 245 million during the river Rhine's low water tides in 2018 because the supply by inland waterway transport became disrupted (BASF SE, 2019; Reuters, 2019) (BASF SE, 2019; Reuters, 2019). The port in Marl, among other ports, could not be accessed for almost two weeks due to ice-coverage of the canal "DHK" in February 2012, inducing significant loss of production capacities to the connected chemical industry park (cf. WSV, 2022; Workshop I, 2019; Workshop II, 2020).

The examples above highlight the dependency of specific SCs on the availability of inland waterways. SC disruptions can propagate downstream of the disrupted SC resulting in risk consequences for additional companies, too (Merz et al., 2009). These consequences are particularly relevant in the case of the (petro-)chemical industry as its products are plentiful and used across industries. For example, a disruption at the chemical park mentioned above caused a shortage of a necessary component for the global automotive industry in 2012. This is why Yan et al. (2015) identify this park as a highly relevant supplier hidden in various multi-tier SCs due to the global effects of the local disruption.

Furthermore, in the field of risk and disaster management, mitigation, prevention and preparedness as part of the pre-disaster phase are highly relevant (Coetzee and van Niekerk, 2012). Therefore, timely and effective early warnings can enable powerful measures and promote the need to identify early warning times (Todd and Todd, 2011). In the considered field of infrastructure failures, this aspect is about time to prepare for disruptions in SCs, such as those caused by scheduled and notified maintenance closures. A prominent example is the port of Dortmund, which could not be accessed by waterway for six weeks in 2019 and will not be again for six weeks in 2020 due to a lock which is permanently under maintenance (WSV, 2022).

B.1.2 Research Objective

This paper aims to investigate the relationship between notification time about restrictions to inland waterway navigability as an enabler for industries to deploy risk mitigation measures. The waterway authority (WSV) announces the restrictions which are targeted to shippers. This allows industries to reorganise their transports, which requires preparation time and enhances the effectiveness of available mitigation strategies to alleviate the effects of the restriction on their affected SCs if necessary. This relationship has not been examined in literature so far.

Assessing the impact of the notification time to SCRM due to restrictions of transport infrastructure is complex because the impact depends on available risk mitigation strategies at the current state of the SC (Tomlin, 2006). Therefore, a mixed-methods approach is suitable. This paper investigates the effects using an exemplary real-world network by obtaining expert knowledge of stakeholders involved in operating the infrastructure. Furthermore, experts of industries are stakeholders who participated in held workshops. The acquired expert knowledge is then compared with the historical notifications about restrictions in the canal system with means of data collection and analysis. This approach allows the authors to draw conclusions about the preparation time of mitigation strategies and to derive an estimate about how logistics operations become affected by the notification time.

Overall, the paper aims to answers the question of what an appropriate level of notification time is. The criterion for this is the possible implementation of measures to ensure SC operations against the risk of infrastructure unavailability. Moreover, this paper defines the critical threshold of notification times at which stakeholders can deploy further mitigation strategies for the unfolding disruptions.

B.1.2.1 Outline

This paper addresses the research question in five sections as follows: First, this paper maps the relevance of notification time into the concepts of risk management and SCRM, thereby describing related and existing works to introduce the topic. Then, the paper establishes its mixed-methodology by setting up the workshop concept firstly. Secondly, the findings of the workshop regarding notification time and their consequences for SC operations are compared to the found situation in the West-German canal system by analysing data of the issued notifications from the authorities. In the following two sections, the paper presents and discusses the obtained results. Finally, the authors link the results to the perspective of SCRM and outline further research steps.

B.1.2.2 Definition

The scientific literature rarely takes into account the discussed notification times. Similar aspects are regarded within the field of disaster management, for example as part of early warning systems. There, the term warning time is more present and is related to the fact that short warning times do not allow effective measures, concerning disasters like natural hazards, to "be implemented in the time available for preventive action and are, therefore, very critical" (Krausmann et al., 2011). To distinguish large-scale disasters from the interruptions considered here, the authors speak of notification times within the research scope. This term transfers the warning time and concepts of disaster management research to the field of SCRM.

B.2 Literature Review

The dependencies between SCRM, underlying transport infrastructure and risk management are investigated in their respective areas of research. The following section first briefly outlines these interdisciplinary approaches before the concept of notification time is classified from disaster management approaches.

B.2.1 Supply Chains and Inland Waterway Transport

Inland waterway transport explicitly in the scope of Supply Chain Management (SCM) is considered in one paper (Achmadi et al., 2018) and one dissertation (Caris, 2011). Pant et al. (2015) quantify the consequences of disruptions of inland waterway ports serving multiple industries with waterway connections to multiple regions by calculating the economic losses of industries. More often, the direct risk associated with navigation of inland cargo vessels is analysed (i.e. Xin et al., 2019; Zhang et al., 2014; Yang et al., 2020). Since the literature on waterway transport seldomly considers the supply chain management perspective and does not consider warning or notification times of possible disruptions, the following two sections elaborate on these aspects.

B.2.2 Supply Chain Risk Management

Risk management is becoming increasingly important in the area of SCM. SC Risk Management (SCRM) is identified as necessary for the agility and robustness of a company and is gaining importance with increasing risks (Wieland and Marcus Wallenburg, 2012). Since a SC comprises companies that want to improve their efficiency and effectiveness by integrating and coordinating the flows of materials, goods, information, knowledge and finance, efficient risk management is of need (Bowersox, 2013). This need reflects risks from SC disruptions, which can be neglected by focussing primarily on cost reductions (Khan et al., 2008).

Tomlin (2006) identifies the significance of mitigation strategies for managing SC disruption risks. Therefore, several research attempts deal with the robustness of SCs (Hosseini et al., 2019; Shukla et al., 2011) as well as with the direct analysis of disruptive effects in SCs (Käki et al., 2015; Kleindorfer and Saad, 2005; Sawik, 2019). Further attempts investigate SC robustness and disruption risks in SCs on the background of a natural disaster (Fujimoto, 2011; Park et al., 2013). Whereas most of this research is focussing on the topology of the SC like single or multi-sourcing structures (Yu et al., 2009), Hosseini and Barker (2016) also analyse timely effects which lead to the resilience of infrastructures. In the latter case, the timely effects are limited to the time after a disruption occurs and therefore does not take into account the time before it occurs. The following section examines time aspects of the pre-disaster phase from disaster management. The concept of notification time is associated with early warning systems, which are also becoming increasingly important in SCs.

Referring to early warning systems, the connection between what is particularly present in the area of natural disasters and the briefly discussed SCRM does not seem that obvious at first sight. Nevertheless, few early warning systems are currently present in SCs. They aim at identifying negative trends or operational risks for SCs as early as possible to prevent a reduction in sales, damage or even bankruptcy. Therefore, both qualitative and quantitative methods can be used, for example, for long-term forecasts of structural changes, with the crucial question being how much time is lost until the measures become effective (Romeike and Brink, 2006).

B.2.3 Notification time in risk management

The field of risk management uses disaster management cycles to explain and manage the impacts of disasters (e.g. Baird, 1975; Coetzee and van Niekerk, 2012; Khan et al., 2008). Their three key stages are namely the pre-disaster phase, the disaster occurrence and the post-disaster phase. They comprise all activities, programs and measures aimed at preventing a disaster, reducing its impact or recovering from its losses (Khan et al., 2008). Apart from this, many attempts of more precise disaster management cycles exist, in which, partly due to the various characteristics of disasters, the phases may overlap and be hard to distinguish (Neal, 1997). As an example, Figure B.1 depicts an early attempt.

The pre-disaster phase is significant since it deals with the predictability of the occurrence of disasters. This mostly includes their unpredictable and precise location, timing, or severity and can include measures like plans for timely and effective early warnings (Todd and Todd, 2011). As phases that need to be considered before the occurrence of a disaster, Figure B.1 shows the aspects of mitigation, prevention, and preparedness as part of the pre-disaster phase (Coetzee and van Niekerk, 2012). Moreover, it shows a phase of warning, which should be taken into account in the management of disasters (Baird, 1975).

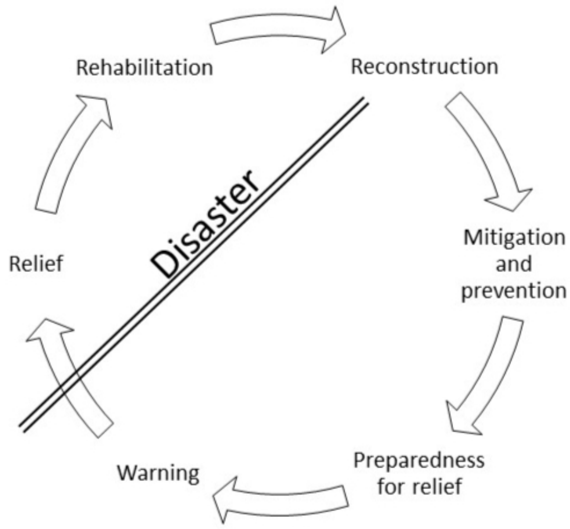

Figure B.1: Disaster management cycle
(adapted from Baird, 1975)

In summary, the research about SCRM mostly neglects the aspect of warning times or notification times, which is why the concept of disaster management is predominantly used instead. The source knowledge from primary literature has to be extended to connect these concepts through the defined notification time and be able to elaborate on the impact of notification time on SC operations.

B.3 Methodology

Expert knowledge is necessary to assess the minimum level as a critical threshold of notification times for inland waterway transport as there are no concepts in SCM about it. However, they may be subject to cognitive or motivational bias, which has to be ad-dressed by the concept and methods of gaining reliable expert knowledge (Miles et al., 2020). These insights from the contributory expertise of the experts can be linked-to in the analysis of empirical data from historical disruptions. This also diminishes the potential bias of the experts due to a quantitative methodology. The workshop and the data analysis together form the mixed-methodology of this paper.

B.3.1 Workshop

Expert knowledge has to be extracted and used to identify appropriate levels of notification time and to be able to deploy SCRM mitigation strategies in case of infrastructure restrictions. Therefore, an interdisciplinary workshop concept is developed by considering an interdisciplinary workshop as an openly structured working meeting with participants from different disciplines, in which different questions can be worked on together by using appropriate techniques (Niederberger and Wassermann, 2015).

The development of the workshop concept must meet certain conditions to benefit from interdisciplinary workshops. These conditions concern, among others, a suitable location and a positive working atmosphere as well as a clear definition of the topic or objective. The composition of the participants also plays an essential role since it influences the arrangement of the points mentioned above (Beermann et al., 2015; Lipp and Will, 2008). One aim was to identify appropriate notification times for infrastructures and, to be suitable for causal research, identify their dependency on reasons for the infrastructure closure. Expert interviews within the held workshop should allow identifying critical thresholds of notification times, which affect maintenance and logistics operations.

Two separate workshops took place ten months apart. The contributions regarding the mentioned sub-target took about half a day each. Six invited participants from all relevant stakeholders attended both workshops; this includes experts from public authorities, science and industry. The groups of participants overlapped but were not identical.

The first workshop served to identify predominantly qualitative correlations. Through open discussions and group work, insights could be gained and manifested, which are essential for the risk assessment of the infrastructures under consideration, including the need to examine the question of appropriate notification times. Interactive discussions and an attempt at gamification were developed and applied to address the risk assessment within the second workshop. In particular, the approach of gamification could manifest insights into the possible mitigation measures that differ in the perspectives of the stakeholders.

Overall, open discussions contributed to identifying essential relationships and processes. Subsequently, the experts were confronted with scenarios and conclusions based on these, which could be falsified, validated or extended by the methods used in the workshop.

B.3.2 Data Analysis

In addition to the workshops, this research elaborates on the relation of the notification time by conducting data analysis about the situation in inland waterway transport. This contributes quantitative insights into the qualitative relationships obtained by the experts.

The notification time for restrictions to inland waterway transport is determined by an analysis of ’Notifications to Skippers’, which is in the following abbreviated as NtS, which are issued by the WSV and are accessible online (WSV, 2022)(ELWIS-database, 2019). NtS are usually targeted to all vessels at the waterway and inform about changes of valid regulations or navigational charts. They also contain temporary directives from the WSV or shipping police that affect navigability and thus are of interest.

NtS contain information about the issuing instance, the date of issuing, the date of validity and date of expiry. Also, the variable interval indicates whether the restriction is valid throughout or only at particular time intervals of a day. The data includes the types of restriction to navigability, the affected group and states a reason. Furthermore, the NtS refers to affected waterway infrastructure

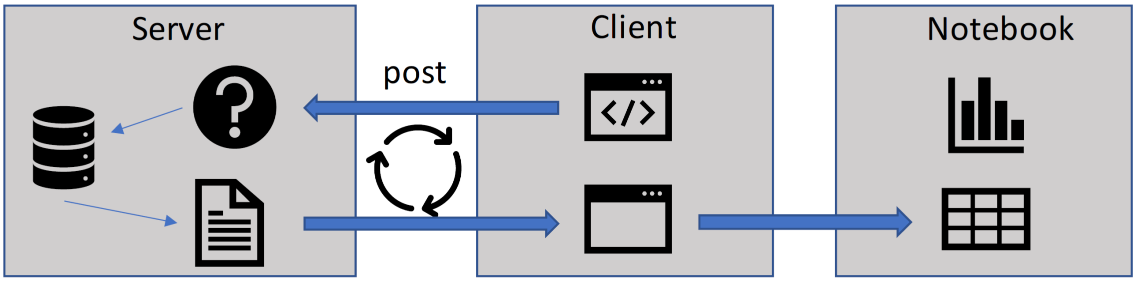

Figure B.2: Schema of the data collection process

objects and their waterway. This enables the analysis of the notification time in which stakeholders can reorganise scheduled transports. Moreover, the NtS contain further information, which allows data drill-downs, like the mean of communication, the range of restriction, the reporting obligation, version number, the issuing instance, and additional information provided by the issuing instance.

Figure B.2 depicts the whole process: The authors collected the NtS individually through the ELWIS-web interface with the python-requests module by using a post-request to the "ELWIS"-server which returns the NtS-document from the database. The document is then fragmented into data entries that are transformed to variables at the client-side with python. The created record has a uniform syntax on the client-side that is appended to the dataset. The dataset is indexed by the ID of the NtS as well as the locations the NtS refers to. The analysis is then performed on this dataset using a jupyter®-notebook.

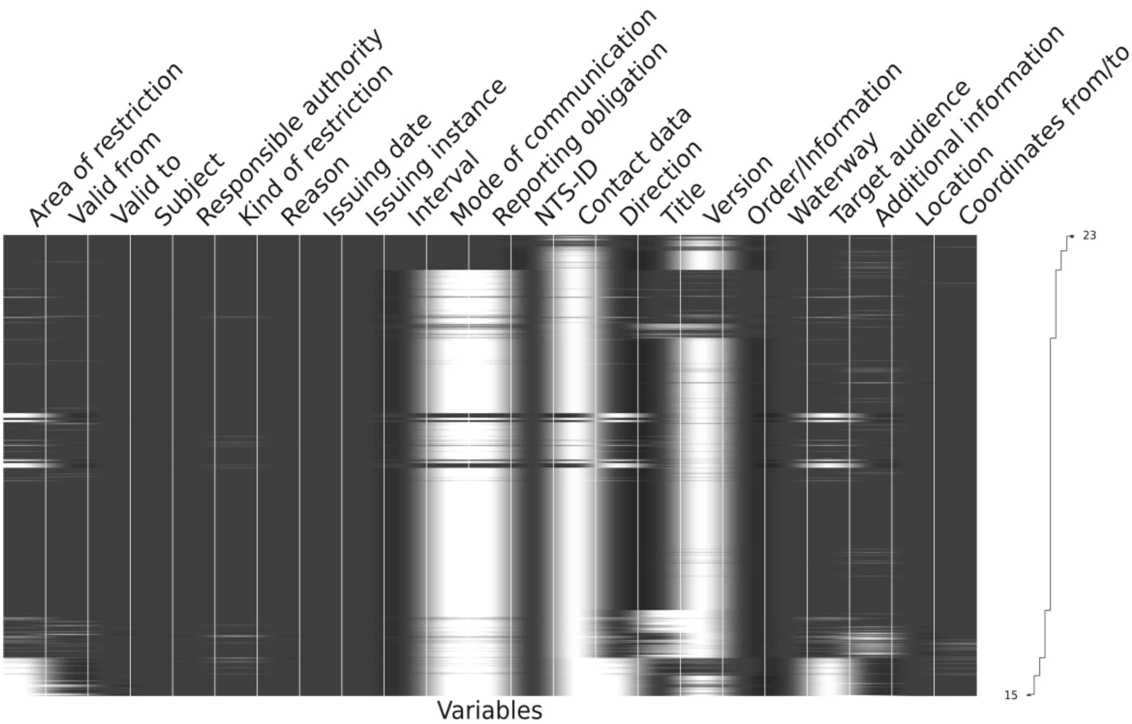

Figure B.3: Overview of variables and completeness of the dataset

The database contains scattered NtS since 2001, albeit continuously since 2007. Overall, the dataset contains 47,425 records and 27 variables. As one NtS-entry can refer to multiple locations, the unique number of NtS totals 39,964. In a first step, only the NtS for the waterways of the West-German canal system is used, dropping the number of records to 3,838.

The records contain information described above and further details separated into the record variables shown in Figure B.3. Most NtS contain a field for additional information specifying the notifications or instructions given by the waterway authorities. The dataset is mostly complete as seen in Figure B.3: Collected data are depicted in dark grey, whereas missing values in the dataset are depicted in white (design by Bilogur, 2018).

Missing information could be completed with further assumptions, which are backed up by the expert knowledge gained from the workshops discussed in Section B.3.1. These are namely the following: The NtS are published as notifications with implication on inland waterway transport and not for informational purposes only, which were dropped before. A missing value of the variable version indicates NtS without further changes to the notification issued by the authority, meaning a version number of 1. If not otherwise stated, the NtS are released by radio (the value is "UKW"). If not otherwise stated in the column Interval, the NtS are valid continuously from the starting date (Valid from) until the date of expiry (Valid to). Twenty-seven records were deemed not relevant.

NtS purely being issued as an informational note or NtS that were being revoked by the WSV are also dropped. This is indicated either in the title or is identified by value mapping and analysis of the types of restrictions. This eventually drops the relevant dataset to 3,102 records. The distribution of the counts of records for the waterways in the West-German canal network over the years is shown in Figure B.4. Not many NtS were issued for the DHK, and there are differences

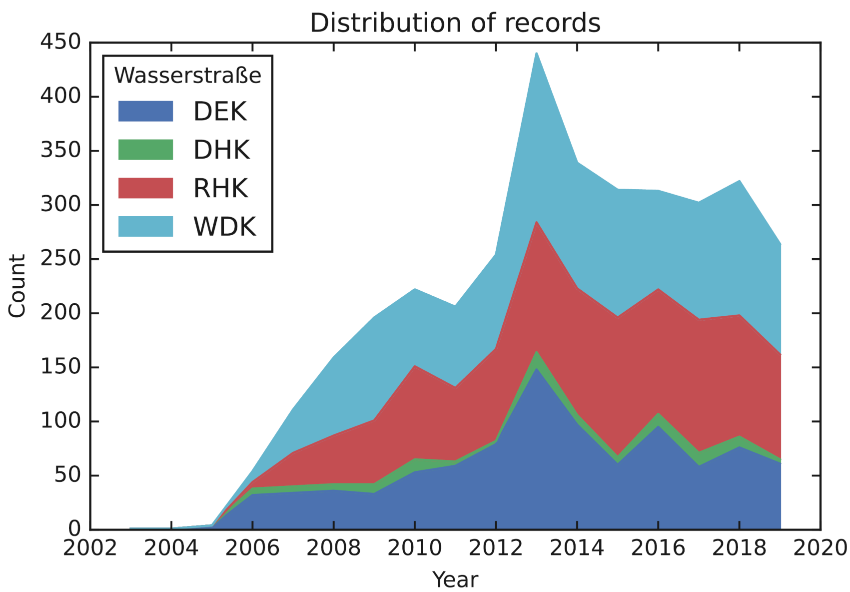

Figure B.4: Distribution of NtS records
(WSV, 2022)

in the number of records across the years. The periodicity of records seems to correlate indicating relationships between the canals. The composition of the findings is stated in Section B.4.2.

B.4 Findings

By using the described mixed-methods approach, several findings could be extracted and validated with different approaches. In the following, the mostly qualitative results of the workshop are highlighted first. Then, the results of the data analysis are presented.

B.4.1 Workshop

The findings of the workshops are referenced to by Workshop I (2019) and Workshop II (2020). One of the findings of the workshop implementation was that the possibilities of the industry as a stakeholder are limited and dependent heavily on the notification time. This is partly due to a bottleneck in the transport capacity of alternative modes of transport. Another restricting factor is the storage capacity, which varies for industries.

Therefore, the possible stock level and production capacity are identified as further limitation factors. Since those identified limitation factors are finite physical values, they are assumed as fixed values for the analysis of the parameter notification time.

Given those fixed values, an average required minimum notification time of two weeks could be identified, as this is likely to enable the procurement of capacities of rail cargo transport. The consequences of long-term disruptions with a notification period of less than this critical threshold contain significant impacts on businesses in the industry surveyed, which is highly dependent on the functioning of inland waterways. This includes supply bottlenecks up to a complete stop of production. The latter is particularly critical if the industry concerned is part of critical infrastructures such as public utilities. Furthermore, no significant pressure in logistics operations is given if the notification time is more than 28 days. This applies to short-term and average restrictions.

Further findings from the workshops reveal that the direct effects of weather are neglectable in waterway canals. However, companies have different SC vulnerabilities to infrastructure closures. Power plants have large storage ranges of up to months so that an early notification time allows for adjusted stockpiling and production planning. Also, road cargo is a possible, albeit costly option. This is not the case for the chemical industry: The storage ranges are within days, and storage is used by both supply and finished products. Hence, this industry needs to maintain a minimum level of access to inland waterway transport during times of temporary restrictions. The information about the interval of the restriction is found in the NtS. Early notification allows for scheduling daily logistics operations more easily to the unrestricted intervals. The strategy of restriction intervals to allow a minimum level of navigability is utilised by the WSV.

Restriction	Count	Notification time [d]		Time to repair [d]	
		Mean	Median	Mean	Median
Closure	1781	22.08	7.0	6.39	0.0
Special caution	535	17.26	4.0	17.23	1.0
Partial closure	369	13.41	5.0	8.16	0.0
One-way only	198	14.02	4.0	59.56	6.0
Restrictions	117	2.50	3.0	5.72	1.0
Operations restricted	78	3.26	0.0	49.67	2.0
Docking ban	71	19.22	3.0	16.9	3.0
Maximum Ship length/width	62	32.40	10.5	80.25	8.0
Delays	49	14.86	6.0	28.94	1.0
Operations changed	46	0.13	0.0	295.3	1.0
Operations closed	26	15.19	5.0	7.77	1.0

Table B.1: Restrictions of the West-German canal system

The mixed-methods approach shows that some of the restrictions have less relevance for inland waterway transport, like closures due to special caution. However, the workshops revealed that even minor delays of less than one hour potentially stack up because the unloading crew at a port might not be able to clear cargo this day anymore, which leads to further delays.

B.4.2 Data Analysis

The data analysis supports the aforementioned findings: The length of most restrictions is less than a day and therefore provide timeframes of navigability. The types of restriction and their average notification, as well as the duration of closures, are reported in Table B.1. It is depicted that the reported mean of notification times for closures is about 22 days and meets the two-week threshold. However, the median is way below (7 days). The variable Time to repair indicates how long the restriction remains. Further findings are outlined in the figures below.

Even though relationship tests, including correlation and hypothesis testing, were conducted between the variables notification time and time to repair, the results show no significance for the entire time scale. This is explained, at least partially, by the large variance of closure times caused by particular accidents requiring repairs lasting over a year. Accidents understandably have a notification time of zero, whereas most disruptions of the waterway infrastructure with varying notification times were fixed within hours.

The statistics of their respective notification times are depicted in the violin graphs in Figure B.5 and Figure B.6, which are scaled by the count of records for each category at the x-axis (design by Waskom et al., 2017). The left side of each violin represents the records where the time to repair was less than a day; the right site depicts the remaining records. Figure B.5 illustrates that the median notification time for closures is about eight days and that 50% of observed values are

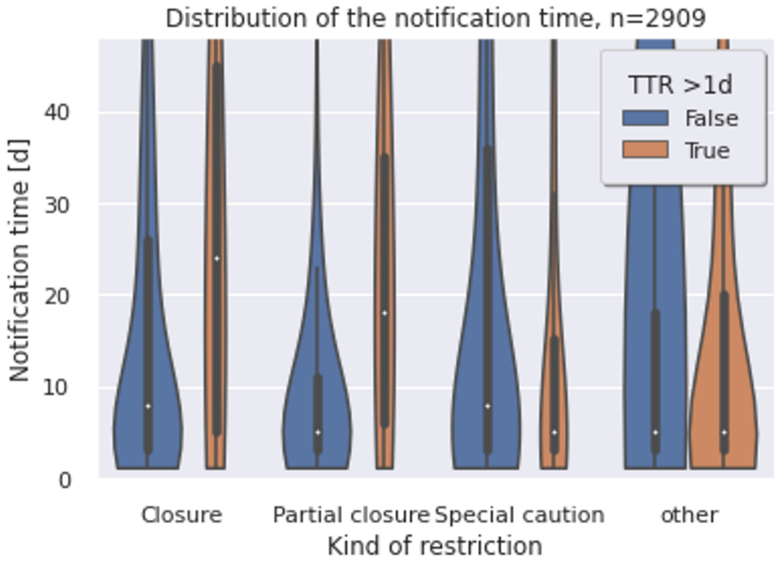

Figure B.5: Distribution of the notification time regarding the type of restriction

between zero and 24 days. For closures that last for longer than a day, the average notification time is 25 days. The average notification time for closures lasting less than a day is significantly lower. This relationship between the medians (white dots) and averages (the middle of the black box of the interquartile ranges) is opposite to the other types of restrictions. This inverse relationship is also partly true for the distribution bandwidth.

Closures due to special cautions and other reasons have much lower notification days of just about four days. Furthermore, differences exist between variables according to the reason of restriction, which is outlined in the scaled violin plot in Figure B.6 which examines the full closures of longer than a day. Interruptions in the availability of these critical infrastructures occur, among

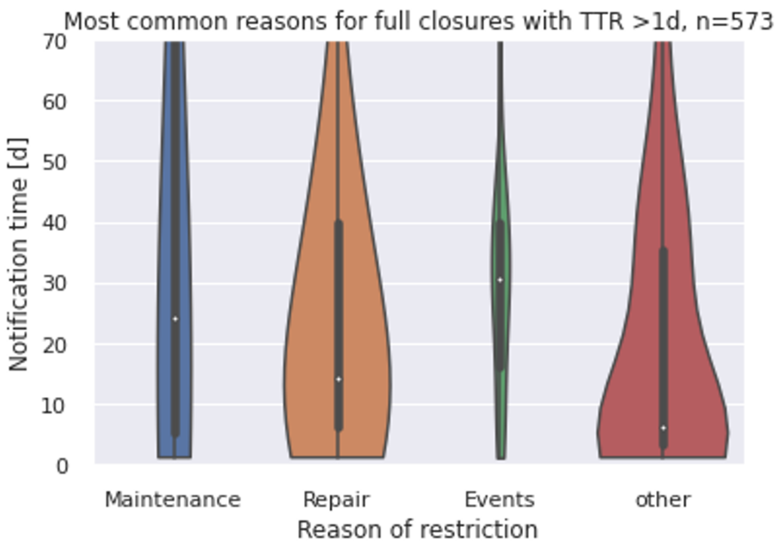

Figure B.6: Distribution of notification time regarding the reason of restriction other things, due to maintenance operations. These have a longer notification time than repairing operations.

B.5 Discussion

The presented research shows an innovative approach to analyse notification time and impact on logistics, which is rarely considered in the literature so far. Whereas expert knowledge within a targeted workshop concept led to findings of processes, industries and mitigation measures, the analysis of historical data could deepen the overall analysis by contributing quantitative findings referring to the notification time. Further correlations between notifications and, on the one hand, industries as well as on the other hand, the infrastructure operators show the significance of respecting possible notification times.

The mixed-methods approach shows that some of the restrictions have less relevance for inland waterway transport, like closures due to special caution. Furthermore, ships in the West-German canal system often drive a roundabout to the seaports, which limits the possibility of earlier procurement, as transport capacities are in transit.

Limitations of the presented research exist primarily in the dependence on the data quality, which is concerning both applied approaches. Since the quality of the expert knowledge collected in workshops depends on many factors, these must be taken into account in order to obtain usable data quality. Furthermore, the data quality and accessibility have a big influence on the results, as well as the quality of assumptions met to complete incomplete records. As accounted for these issues in the data processing steps, this is leading to a reduced number of observations. Overall, however, it can be stated that the data situation in the study area can be regarded as solid. All possible disturbance variables were taken into account in the workshop design, and the data analysis is based on further implications of the extracted expert knowledge.

B.6 Conclusion

The research reveals a high impact of the notification time on logistics operations in inland waterway transport and reveals the planning reliability for all parties involved. Restrictions that heavily affect navigability, closures, are either tried to be limited to hours at a day or notified in advance. The mixed-methods approach found that the notification time for the majority of the considered short-term restrictions ($1>$ day) is below the identified critical threshold. As these pose threats to SC operations, SC planning must account for these restrictions.

This research is innovative as there is little analysis on inland waterway transport, even though accessible historical data exists, and inland waterway transport is relevant for particular industries. This research contributes to the literature by linking critical infrastructure, expert knowledge, and SC operations. Quantitative methods provide the base of broad possibilities for interdisciplinary research. Furthermore, the presented analyses can be used to support SC and infrastructure monitoring processes to account for different risk mitigation strategies depending on the notification time.

Further research could integrate the notification time in the concept of SC resilience, where recovery time is prominent, as they are related as the disaster management cycle in Figure B.1 suggests. Also, further research could investigate changes in SC operations due to notification time or the restrictions itself by data analysis of inland AIS-data, which tracks ship movements.

Acknowledgements

The authors want to thank the partners in the joint research project PREVIEW. The project is funded by the security research fund of transportation infrastructure (SIFO) of the German Federal Ministry of Education and Research (BMBF). Special thanks go to the WSV Duisburg-Meiderich, who shared their expertise, thereby supporting this research.

References

Achmadi, T., Nur, H. I., Rahmadhon, L. R. (2018). Analysis of inland waterway transport for container shipping: Cikarang to port of tanjungpriok. *IOP Conference Series: Earth and Environmental Science*, *135*, 012015.

Baird, A. (1975). Towards an Explanation and Reduction of Disaster Proneness.

BASF SE. (2019). *BASF Report 2018*. Retrieved 04.08.2019, from `http://www.basf.com/cz/documents/BASF_Report_2018.pdf`

Beermann, S., Augart, E., Schubach, M. (2015). *Workshops: Vorbereiten, Durchführen, Nachbereiten*. Freiburg: Haufe-Lexware GmbH & Co. KG.

Bilogur, A. (2018). Missingno: A Missing Data Visualization Suite. *The Journal of Open Source Software*, *3*(22), 547.

Bowersox, D. J. (2013). *Supply Chain Logistics Management* (4th ed.). New York, NY: McGraw-Hill.

Caris, A. (2011). Simulation and Optimisation of Intermodal Barge Transport Networks. *4OR*, *9*(2), 211–214.

Coetzee, C., van Niekerk, D. (2012). Tracking the Evolution of the Disaster Man-agement Cycle: A General System Theory Approach. *Jàmbá: Journal of Disaster Risk Studies*, *4*(1).

ELWIS-database. (2019). Retrieved 17.05.2019, from `http://www.elwis.de`

Faertes, D. (2015). Reliability of Supply Chains and Business Continuity Management. *Procedia Computer Science*, *55*, 1400–1409.

Federal Statistical Office of Germany (Ed.). (2019). *Fachserie Binnenschifffahrt*. Retrieved from `http://www.genesis.destatis.de`

Fujimoto, T. (2011). *Supply Chain Competitiveness and Robustness: A Lesson from the 2011 Tohoku Earthquake and Supply Chain "Virtual Dualization"*.

Gast, J., Wehrle, R., Wiens, M., Schultmann, F. (2020). Impact of Notification Time on Risk Mitigation in Inland Waterway Transport. *Hamburg International Conference of Logistics (HICL)*(2020).

Hosseini, S., Barker, K. (2016). Modeling Infrastructure Resilience using Bayesian Networks: A Case Study of Inland Waterway Ports. *Computers & Industrial Engineering*, *93*(7), 252–266.

Hosseini, S., Ivanov, D., Dolgui, A. (2019). Review of Quantitative Methods for Supply Chain Resilience Analysis. *Transportation Research Part E: Logistics and Transportation Review*, *125*, 285–307.

Käki, A., Salo, A., Talluri, S. (2015). Disruptions in Supply Networks: A Probabilistic Risk Assessment Approach. *Journal of Business Logistics*, *36*(3), 273–287.

Khan, H., Vasilescu, L. G., Khan, A. (2008). Disaster Management Cycle – a Theoretical Approach. *Management and Marketing Journal*, *6*(1), 43–50.

Kleindorfer, P. R., Saad, G. H. (2005). Managing Disruption Risks in Supply Chains. *Production and Operations Management*, *14*(1), 53–68.

Krausmann, E., Cozzani, V., Salzano, E., Renni, E. (2011). Industrial Accidents Triggered by Natural Hazards: An Emerging Risk Issue. *Natural Hazards and Earth System Sciences*, *11*(3), 921–929.

Li, G., Lin, Y., Wang, S., Yan, H. (2006). Enhancing agility by timely sharing of supply information. *Supply Chain Management: An International Journal*, *11*(5), 425–435.

Lipp, U., Will, H. (2008). *Das große Workshop-Buch: Konzeption, Inszenierung und Moderation von Klausuren, Besprechungen und Seminaren* (8th ed.). Weinheim and Basel: Beltz Verlag.

Merz, M., Hiete, M., Bertsch, V. (2009). Multicriteria Decision Support for Business Continuity Planning in the Event of Critical Infrastructure Disruptions. *International Journal of Critical Infrastructures*, *5*(1/2), 156.

Miles, M. B., Huberman, A. M., Saldaña, J. (2020). *Qualitative Data Analysis: A Methods Sourcebook* (4th ed.).

Neal, D. (1997). Reconsidering the Phases of Disaster. *International Journal of Mass Emergencies and Disasters*, *15*(2).

Niederberger, M., Wassermann, S. (Eds.). (2015). *Methoden der Experten- und Stakeholdereinbindung in der sozialwissenschaftlichen Forschung*. Wiesbaden: Springer VS.

Pant, R., Barker, K., Landers, T. L. (2015). Dynamic Impacts of Commodity Flow Disruptions in Inland Waterway Networks. *Computers & Industrial Engineering*, *89*(2), 137–149.

Park, Y., Hong, P., Roh, J. J. (2013). Supply Chain Lessons from the Catastrophic Natural Disaster in Japan. *Business Horizons*, *56*(1), 75–85.

Reuters (Ed.). (2019). *"BASF Says It Has Prepared for Any Repeat of Low Rhine Water Levels - Reuters"*. Retrieved from `www.reuters.com/article/us-basf-results-rhine/basf-says-it-has-prepared-for-any-repeat-of-low-rhine-water-levels-idUSKCN1S90LZ`

Romeike, F., Brink, G. J. (2006). Frühwarnindikatoren: Kritischer Faktor Spätwarnung: Erkennung von Trends und Frühen Signalen im Risikomanagement. *Risiko Manager*(13), 4–10.

Sawik, T. (2019). Disruption Mitigation and Recovery in Supply Chains Using Portfolio Approach. *Omega*, *84*, 232–248.

Shukla, A., Agarwal Lalit, V., Venkatasubramanian, V. (2011). Optimizing Efficiency–Robustness Trade–Offs in Supply Chain Design under Uncertainty due to Disruptions. *International Journal of Physical Distribution & Logistics Management*, *41*(6), 623–647.

Todd, D., Todd, H. (2011). Natural Disaster Response. *World Bank Publications*.

Tomlin, B. (2006). On the Value of Mitigation and Contingency Strategies for Managing Supply Chain Disruption Risks. *Management Science*, *52*(5), 639–657.

Waskom, M., Botvinnik, O., et al. (2017). Mwaskom/Seaborn: V0.8.1 (September 2017).

Wieland, A., Marcus Wallenburg, C. (2012). Dealing With Supply Chain Risks. *International Journal of Physical Distribution & Logistics Management*, *42*(10), 887–905.

Workshop I. (2019). *Project: PREVIEW.* Karlsruhe. Retrieved from `www.preview-projekt.de`

Workshop II. (2020). *Project: PREVIEW.* Karlsruhe. Retrieved from `www.preview-projekt.de`

Xin, X., Liu, K., Yang, X., Yuan, Z., Zhang, J. (2019). A simulation model for ship navigation in the "xiazhimen" waterway based on statistical analysis of ais data. *Ocean Engineering*, *180*, 279–289.

Yan, T., Choi, T. Y., Kim, Y., Yang, Y. (2015). A Theory of the Nexus Supplier: A Critical Supplier From A Network Perspective. *Journal of Supply Chain Management*, *51*(1), 52–66.

Yang, L., Xing, Z., Shi, T. (2020). Risk Assessment of Ship Navigation Collision in Inland Waterway Transportation System Based on Bayesian Method. *IOP Conference Series: Materials Science and Engineering*, *780*(6), 062018.

Yu, H., Zeng, A. Z., Zhao, L. (2009). Single or Dual Sourcing: Decision-Making in the Presence of Supply Chain Disruption Risks. *Omega*, *37*(4), 788–800.

Zhang, D., Xinping, Y., Zaili, Y., Jin, W. (2014). An Accident Data-Based Approach for Congestion Risk Assessment of Inland Waterways: A Yangtze River Case. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, *228*(2), 176–188.

C Economic risk potential of infrastructure failure considering inland waterways

Abstract[1]

Purpose - Unreliability of transport infrastructure can cause negative externalities for industries. In this article, we analyze how the private sector is affected by infrastructure failure of public transport infrastructure, using waterways as an example.
Methodology - To investigate the affectedness of riparian industries, we choose two complementary parallel approaches: A proximity analysis via GIS and a concluding survey among the identified waterway-dependent industries. An exemplary application is validated by stakeholders.
Findings - We identify a predominance of location preferences in dependence of waterways for mining, chemical, and metal industries. Their risk tolerance exhibits potentially severe impacts on industries if reliable transports cannot be ensured via waterways, as our paper provides essential insights into the relationships between infrastructure failure and company decisions. Most importantly, we reveal that a lack of alternatives due to missing capacities of other transport modes causes realistic threats to business locations.
Practical implications - A regional focus is crucial for the empirical risk assessment of transport infrastructure. Hence, the data collection should relate to the regional focus groups, particularly the directly affected industries. In addition, infrastructure maintenance should integrate a risk focus and consider the short and long-run impacts on industries.

Keywords: Waterways, Empirical, GIS, Location analysis, Risk perception

C.1 Introduction

Transport infrastructure as backbone of modern societies is characterized by interdependencies among infrastructures (Rinaldi et al., 2001), whereas threats of all kinds can lead to systemic and

[1] This chapter includes the preprint of the article "Economic risk potential of infrastructure failure considering inland waterways" by Marcus Wiens, Fabian Neff, Frank Schultmann, and myself (Wehrle, Wiens, Neff, and Schultmann, 2022).

cascading risks (Buldyrev et al., 2010). Possible threats are catastrophic events like natural disasters or terrorist attacks, but can also arise from human-technical failure, where neglected maintenance may exacerbates critical impacts of catastrophic events.

The example of Inland Waterway Transport (IWT) as barely studied type of infrastructure demonstrates a potentially dangerous, systemic set of problems in the asset stocks of transport infrastructure, which results in a steadily deteriorating condition of existing transportation infrastructures as can be observed all over the world (Federal Ministry for Digital and Transport, 2019; Hosseini and Barker, 2016; Kotowska et al., 2018; Wang and Schonfeld, 2005).

A deteriorating transport infrastructure mostly affects the neighboring industries, since cargo has to be shifted to other modes of transport, and urgently needed goods experience delivery problems. Depending on the type of goods, different industries can be affected in different ways, such as electricity supply versus chemical products, for example.

As a consequence, deteriorating construction assets pose a threat to business locations (Oztanriseven and Nachtmann, 2020), necessitating the effective deployment of scarce maintenance resources in order to support local business activities. Therefore, we aim to assess the impact on the economy that can be expected by infrastructure failure. We state the key questions of our research:

(1) Which industries and company-locations are directly affected by IWT failure?
(2) What business decisions may result from lasting availability reductions of IWT?

The paper is structured as follows: We first deepen our motivation within a literature review about the risk assessment of transport infrastructure and the interdependencies toward Supply Chains (SCs) in the following section. Based on this, we derive and apply methods to understand risk perception and decisions of companies resulting from infrastructure damage (Section C.3.2). This includes GIS-based proximity analyses, a survey and the application of expert interviews. The developed methodology is applied to a case study in Germany in Section C.4 to highlight the feasibility and relevance of the approach. Finally, we elaborate on the findings and conclude with a critical discussion.

C.2 Literature Review

C.2.1 Externalities of transport infrastructure

Externalities arise from economic decisions and activities having an uncompensated impact on uninvolved parties. Negative externalities of transport include road damage, accidents, congestion, oil dependence and environmental externalities as pollution (Janic, 2000; Ranieri et al., 2018; Santos et al., 2010). Further externalities can be observed concerning house prices and rents (Dubé et al., 2013; Efthymiou and Antoniou, 2013), while only few studies concern waterways, but they are focused on maritime transport (Vierth and Merkel, 2020).

Nevertheless, effects toward riparian industries are neglected in literature, which is why we examine the externalities caused by infrastructure failure to commercial transport. Previous studies about impacts of infrastructure developments on economic productivity are primarily considered only from a growth perspective (Deng, 2013; Hulten et al., 2006; Knowles and Ferbrache, 2016), revealing positive externalities of infrastructure investments such as the productivity of firms and economic agglomeration (Eberts and McMillen, 1999; Graham, 2007).

Bernacki and Lis (2021) provide one of few studies on water-based transport and calculate savings of travel times caused by improved seaport infrastructure. Nevertheless, external costs of infrastructure use and provision do not comprise externalities of unavailable infrastructure. To this end, negative externalities were analyzed for foremost road and railways transport. However, to the best of our knowledge, the nexus between infrastructure unavailability of waterways and resulting economic cost for directly affected industries has not been investigated so far.

C.2.2 Risk assessment of transport infrastructure

C.2.2.1 Inland Waterway Transport

While IWT is of great importance in nearly every country of the world (Oztanriseven and Nachtmann, 2020; Rohács and Simongáti, 2007), we focus on Germany as an example region, Approximately 18 million tons of goods are transported on German waterways monthly (Federal Statistical Office of Germany, 2019), while further existing capacity reserves must be used in the future to shift traffic from road to IWT, since it is a comparatively environment-friendly mode of transport (Kotowska et al., 2018; Rohács and Simongáti, 2007). IWT thus represents an elementary component of German and European logistics chains that at the same time serves regional water management in the areas of drinking and service water supply, irrigation, power plant utilization and wastewater disposal, as well as flood protection for the riparians. Furthermore, waterways fulfill an ecological biotope function and have a high recreational value for people (Oztanriseven and Nachtmann, 2020).

IWT is a reliable mode of transport when it is in normal operation (Federal Ministry for Digital and Transport, 2019), assuming the full functionality of the infrastructure and thus of all structures involved, for which predominately government and administration is responsible. However, structures that are system-relevant for the operation of inland navigation are in an increasingly poor condition. They are characterized by a massive maintenance backlog caused by a long-lasting investment deficit (BMVI, 2019). In 2015, for example, around 85 percent of locks, 73 percent of weirs and 87 percent of pumping stations were in an inadequate state of repair (Federal Ministry for Digital and Transport, 2015).

C.2.2.2 Criticality assessment of IWT

IWT as part of the critical infrastructures (CIs) provide fundamental services that are substantial to the safety as well as economic and social welfare of a society (Rinaldi et al., 2001). While vulnerability refers to the hazard-specific susceptibility of a system to impairment or failure of its functionality (Lenz, 2009)(Lenz, 2009), the resulting criticality refers exclusively to the consequences of a system failure, independent of the probability of occurrence (Fekete, 2011).

Harmful consequences of impaired infrastructure as negative externalities refer to various dimensions of criticality, such as the economic, the structural, the social as well as the ecological dimension (Federal Ministry of the Interior and Community, 2011). In this paper, we address the economic dimension of criticality.

Theoharidou et al. (2009) focus more on societal impacts than on economic consequences, while their scenario-based risk quantification is done via a psychometric 4-point Likert scale, which is weighted based on various literature reviews, expert opinions and statistics. Utne et al. (2011) use the parameters frequency, probability, extent and duration to assess the risk of CI, assuming an infrastructure failure as an initializing scenario leading to a subsequent loss of one or more societal critical function(s). Ukkusuri and Yushimito (2009) assess the criticality of highway transportation networks considering congestion effects caused by the interaction of traveler behavior and the built environment (Ukkusuri and Yushimito, 2009). Novotný et al. (2015), moreover, take into account the interactions of different CI sectors.

There are just few approaches, which come close to our research objective, the assessment of economic risk potential resulting from infrastructure failure of IWT. Among the notable exceptions is Wehrle et al. (2020), who reflect the System-of-Systems character of IWT within a risk assessment framework based on a multi-level approach, which allows to integrate both structural vulnerability and empirical research as economic risk potential. Conversely, our research aims at a micro-level approach, which examines and integrates corporate decisions in order to be able to derive macro-perspective conclusions.

C.2.3 Supply Chain Management and dependency on transport infrastructure

To assess an economic risk potential resulting from infrastructure failure, it is important to first understand industrial vulnerability and criticality in order to identify affected industries and their reactions toward disruptive events. Therefore, we elaborate on SC risk management (SCRM) and impacts of disrupted transport infrastructure on SCs, before we come to proximity analyses to figure out concerned industrial sectors.

C.2.3.1 Supply chain risk management and risks as disruptive events

SC is a system consisting of several companies that are directly or indirectly involved in the fulfillment of customer needs and thus include not only manufacturers and suppliers, but also transport service providers, wholesalers and retailers, and as well as customers. The linkage of the enterprises comes about through the flow orientation, i.e. by the flow of information, money and goods (Chopra and Meindl, 2007). SCRM as a specific domain of SC Management is responsible to identify risks, assess possible damages and reduce and mitigate the impacts of threats to the SC using control measures (Khan and Burnes, 2007; Zsidisin, 2003).

SC risks relate to a possible discrepancy between supply and demand and the resulting consequences and may arise from three different risk sources: (1) environment-related risks, which arise due to the interaction of the supply chain with the environment (e.g. floods, terrorist attacks etc.), (2) organisational risks within the boundary of the chain (e.g. strikes or machine failure), and (3) network-related risks that occur due to interactions of firms within the supply chain (Jüttner et al., 2003). Since SCRM aims to enhance and ensure resilient SCs, possible disruptive events must be handled as risks, whereas infrastructure disruptions can be classified as network-related risk, according to Jüttner et al. (2003).

Furthermore, SC risks include procurement and sales risks, among others, while we set the focus on transport risks and the interdependencies between risks. Apart from unavailable infrastructure transport risks mostly affect procurement and sales risks, since freight cannot be transported in due time. Regarding these interconnected risks, it must be noted that infrastructure is the most important factor in logistics performance of companies (Rezaei et al., 2018). Thus, measures to enhance logistics performance and to reduce threats to this performance, infrastructure must take a significant role within the scope of companies SCRM.

C.2.3.2 Proximity of business locations and transport infrastructure

In order to determine the industrial risks of failing transportation infrastructures, it is initially important to analyze which companies are dependent on them, leading to sub-question *(1) Which industries and company-locations are directly affected by IWT failure?* This can be done, on the one hand, by using freight transport statistics, which, however, do not allow any conclusions to be drawn about specific companies. Therefore it is necessary to have a closer look at specific locations and their accessibility to various infrastructures.

Location decisions are long-term investments and thus of great importance in the strategic planning of companies (Owen and Daskin, 1998), since transport links have an important role in the location decision of industrial companies (Holl, 2004). Depending on the industry, industrial companies prefer different means of transport for freight traffic (García-Menéndez et al., 2004). While the topics of company location decisions and freight transportation mode choice are widely studied in research, their interrelationship, in contrast, has been barely studied, as illustrated by Table C.1.

A closer look reveals that most of the literature on distance determination of infrastructures to companies refers to passenger transport, rather than freight transport (de Bok, 2009; de Bok and Sanders, 2005; de Bok and van Oort, 2011). Thomas et al. (2003) consider only freight transport, but do not calculate the distance to the access points of the transport systems, instead assessing the accessibility of Belgian regions on the basis of distances in the road, rail and waterway network.

Literature	Location planning	Transportation choic	Spatial structure	Company	Branch	Access points	Distance measurement	Goods
Bierwirth et al. (2012)		×		×				×
Meixell and Norbis (2008)		×		×				×
SteadieSeifi et al. (2014)		×		×				×
García-Menéndez et al. (2004)		×		×	×			×
Zotti and Danielis (2004)		×		×				×
Arunotayanun and Polak (2011)		×		×	×*			×
Oum (1979)		×		×	×*			×
Bolis and Maggi (2003)		×		×	×*			×
Malmberg and Maskell (1997)			×	×			×	
Carboni (2013)			×	×			×	
Vedovello (1997)			×	×			×	
Mulley et al. (2016)						×	×	
Jin et al. (2010)						×	×	
Coetzee and Swanepoel (2017)	×		×	×	×	×		×
Button et al. (1995)	×			×		×		
McCalla et al. (2001)	×	×	×	×		×		×
Shukla and Waddell (1991)	×		×	×	×	×	×	
de Bok (2009)	×		×	×	×	×	×	
de Bok and van Oort (2011)	×		×	×	×	×	×	
de Bok and Sanders (2005)	×		×	×	×	×	×	
Mejia-Dorantes et al. (2012)	×		×	×	×	×	×	
Thomas et al. (2003)			×			×**	×	×

* Differentiation of goods segments instead of industries

** Consideration of transport networks instead of access points

Table C.1: Literature concerning business locations and proximity to transport infrastructure

C.2.3.3 Impact of transport disruptions on business activities

After the identification of sectors concerned, we want to understand, which kind of business decisions may result from infrastructure failure of waterways. This objective is summarized by sub-question *(2) What business decisions may result from lasting availability reductions of IWT?*

Therefore, procedures, occurrence and impacts of IWT disturbances must be examined. Existing evidence reveals that larger disturbances of waterways occur again and again, such as blockades of the Suez Canal (Huth and Romeike, 2016), while 12% of the world's total ocean trade traverse the Suez Canal (New Zealand Ministry of Foreign Affairs and Trade, 2021). Among others, Sony faced a combination of miscalculation and delivery delay, which caused a 90% decrease of the PlayStation2 sales volume in Great Britain (Elliott and Theodoulou, 2004) and a blockade in 2021 reveals blocking costs of $400 million per hour (Larocco, 2021).

Impacts of disrupted SCs can be classified in (1) direct, i.e. physical damages, and (2) indirect effects, which include all ripple effects. Whereas direct effects in a water-related context rather arise from floods, since the effects include destroyed inventory or machines, infrastructure failure is assigned to the indirect effects (Haraguchi and Lall, 2015).

Measures of SCRM involve changes in the SC structure and the choice of transportation routes and means (Craighead et al., 2007). toward a more resilient SC, SC visibility should be increased, buffer capacities could be enhanced and companies could consider to reorganize the structure of the SC, like going from single-sourcing to multi-sourcing or to consider the use of more generic input components (Fujimoto, 2011; Ivanov and Dolgui, 2019; Lücker et al., 2019). While alternative routing may be sufficient for short-term disruptions, there is in most cases no feasible solution in the long-term such as shifting IWT cargo toward other means of transport, which are regularly capacity-restricted.

For specific goods it is possible to become independent from public infrastructure, as via own pipelines (Park et al., 2013). However, for most industries and goods this is no feasible option.

As a matter of fact, maintaining highly infrastructure-dependent facilities can be more costly than relocating it to another site (Farahani et al., 2009). This can especially come into focus when companies are faced with degrading infrastructure, since reliable transport infrastructure plays an important role in companies' location decisions and is the most important factor in logistics performance (Mejia-Dorantes et al., 2012; Rezaei et al., 2018).

Literature revolving this problem and the scoping of corporate decisions can be found in the field of SC-Management and more specifically in the fields of risk and crisis management dealing with SC disruptions. The last can be caused by pandemics, terrorist attacks, labor strikes, man-made defections for example and can cause production or transportation stops (Lim et al., 2013). Literature about strategical implications like location planning is rather scarce (Cui et al., 2010; Snyder et al., 2016; Snyder and Daskin, 2005) and existing research in this area often neglects the context to short-term disruptions since mostly supplier network design is emphasized (Wu et al., 2007; Yu et al., 2009). Moreover, external influencing factors find little attention.

By extending the literature research toward Facility Location Planning (FLP) and transport infrastructure, we encounter a focus on spatial structure of companies and infrastructure as well as on location(s) for new site(s) rather than on the relocation of existing facilities (Button et al., 1995; Coetzee and Swanepoel, 2017; McCalla et al., 2001; Shukla and Waddell, 1991). Moreover, literature about relocation of facilities meanwhile arose but it is still scarce with regard to infrastructural aspects focusing more on accessibility as predominant infrastructure factor in relocation decisions (de Bok, 2009; Boloori Arabani and Farahani, 2012).

C.3 Research Methodology

C.3.1 Concept

Our methodological approach determines the economic risk potential of unavailable IWT. In particular, we analyze potential impacts of infrastructure failure on the economy, using a GIS-based proximity analysis and empirical studies, namely a survey, supplemented by expert interviews, to achieve background information about corporate decisions and risk perception.

C.3.2 Economic risk potential

To assess economic risks resulting from infrastructure failure, it is first of all essential to assess the general hazard potential of the infrastructure in the (supra-)regional area with regard to the industry. We suggest a combined approach of a proximity analysis of facilities toward infrastructure access points (APs) to identify dependent industry facilities and empirical studies to elaborate on data and background of self-reported industrial vulnerability and criticality.

C.3.2.1 Proximity analysis

According to our first research question (Which companies are directly affected?) we analyze which business facilities rely on IWT by an analysis of spatial proximity based on the relationship between location decisions, spatial structure and modal choice of freight transport across all modes of transport.

Location preferences of industrial facilities are determined depending on the affiliation to industrial sectors and are based on the central assumption that higher preferences correlate negatively with the distance between industrial sites and transport system APs. To assess spatial proximity, the distance between industrial sites and transport system APs is calculated using geographic information systems (GIS). Figure C.1 illustrates the process, which is explained in more detail in the following.

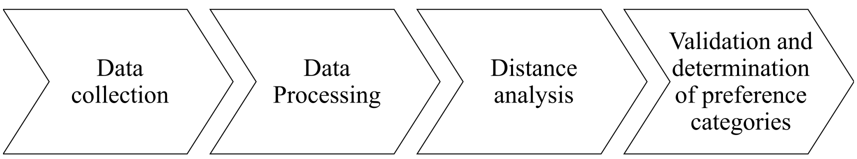

Figure C.1: Process of proximity analysis

Firstly, network data and location coordinates of the APs of further transport systems as well as data about industrial sites are collected, containing locations and industry classifications in the area of interest. In Step 2, the edges of the network are assigned travel times as edge weights, calculated by route lengths and assumptions regarding the average speed of infrastructure categories.

The distance analysis (Step 3) is performed using Dijkstra's algorithm to calculate the shortest travel times for given start nodes (industrial sites) and destination nodes (infrastructure APs: highway interchanges, rail-road terminals, public ports, and airports; radius consideration of company-owned railway and ports).

For each industry, the mode-specific average travel time $\bar{t}_m$ from companies to APs of transport mode m is calculated and taken as a measure of spatial proximity, of which the preferences of the industries for the transport systems are derived in Step 4: By identifying correlations between the industry-specific averages of travel times and the transport volumes from freight statistics, conclusions can be drawn, whether shorter travel times actually correspond to a higher preference in use. For each transport system, preference categories are derived, using the relative deviation from the mean value of the travel times of all industries:

$$IB_{i,j,m} = (1 + d_{i,j}) \cdot \bar{t}_m \qquad \text{(Exp. C.1)}$$

The interval boundary $\mathrm{IB}_{i,j,m}$ indicates the value of the travel time that delimits category i from category j, using $\bar{t}_m$ Thus, negative values for the relative deviations $d_{i,j}$ mean shorter travel times compared to the average and thus correspond to a higher preference. If a validation with freight goods statistics reveals many inconsistencies of the achieved classification, no preferences can be derived for the transport system under consideration. Otherwise it is possible to derive preferences, shown by the classification into the preference categories.

By this procedure, it is possible to identify sectors with particularly high preferences representing sectors which (1) are strongly dependent on specific infrastructure and their APs and (2) indicate corresponding location preferences in the survey. Accordingly, the sectors with preference for IWT are most affected by interruptions and need special attention in understanding the influence of disruptions on business decisions regarding IWT disruptions.

C.3.2.2 Empirical studies

After reflecting location preferences of companies on a macroscopic level to identify concerned industries, we address sub-question *(2) What business decisions may result from lasting availability reductions of IWT?*

Since business decisions like modal shifts or (re-)locations of facilities have significant impacts on business locations, it is essential to understand the interconnections between infrastructure disruptions and business decisions. Therefore, we propose to proceed as illustrated by Figure C.2: Firstly, formulate key questions and derive hypotheses. In a second Step, address these using an (online) questionnaire, containing quantitatively and qualitatively evaluable questions, to gather further data directly from decision makers of companies. In the context of industrial criticality, we examine the following two key questions: (1) How do companies perceive a decrease in availability of IWT and (2) How does this affect their business activities?

Beyond the survey, more in-depth knowledge about motives and experiences are gathered through targeted expert interviews with survey participants, addressing the formulated hypotheses while

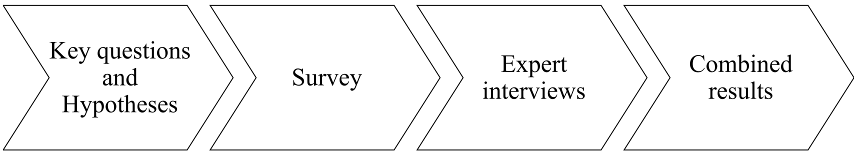

Figure C.2: Process of empirical studies

maintaining the reference to the questionnaire (Step 3). In a last Step (4), the results of survey and interviews are combined to provide deeper insights into use-cause-relations.

C.4 Case

We apply our methodology to the area of the West German Canal Network, consisting of 350 kilometers of canals connecting the Ruhr area and the German North Sea ports (WSA Westdeutsche Kanäle, 2022). In 2013, the volume of goods transported in the West German canal network amounted to approximately 226.8 million freight tons, which corresponds to 37.1% of the total waterborne transport volume in Germany (Federal Waterways and Shipping Agency of Germany, 2014). Moreover, the region of North Rhine-Westphalia (NRW) is characterized by a comparatively high population density and a significant economic importance, which was mainly due to two sectors, coal mines and steel industry.

C.4.1 Economic risk potential

C.4.1.1 Proximity analysis

C.4.1.1.1 Data collection and processing

The selected modelling region causes a limitation for the analysis of companies in NRW, with OpenStreetMap (OpenStreetMap Foundation, 2019) being the main source for data collection. Data about industrial sites is filtered manually and supplemented with information on the industrial classification from Table C.2 (Federal Statistical Office of Germany, 2008). Table C.2, moreover, shows the numbers of company locations considered with a total of 2,823, which are illustrated in Figure C.3.

Peripheral infrastructure was also captured with road network data extracted from Geofabrik GmbH (2020) as Figure C.4 and Figure C.5 visualize, extended by data sources for railways and rail-road terminals (Deutsche Umschlaggesellschaft Schiene - Straße (DUSS) mbH, 2017) and track connections. The latter pose APs for specifically located companies, which could be extracted from OSM via the Overpass API (Application Programming Interface) (OpenStreetMap Foundation, 2019).

The track connections and rail-road terminals are depicted in Figure C.6. Analogously, the data on ports was extracted, as shown in Figure C.7, whereas airport locations were added manually.

For better orientation and comparability of Figure C.3, C.4, C.5, C.6 and C.7, the cities of Duisburg and Hannover were drawn in the maps.

Category	Name	Section*	Division*	Number
B	Mining and quarrying	B	all	44
C1	Production of food and feed, beverage production	C	10, 11	137
C2	Coking plant and mineral oil processing	C	19	15
C3	Production of chemical and pharmaceutical products	C	20, 21	61
C4	Manufacture of rubber and plastic products	C	22	80
C5	Manufacture of glassware, ceramics, processing of stones and earths	C	23	118
C6	Metal production and processing	C	24	59
C7	Production of metal products	C	25	325
C8	Manufacture of computer, electronic and optical products, manufacture of electrical equipment	C	26, 27	106
C9	Mechanical Engineering	C	28	238
C10	Manufacture of motor vehicles and parts of motor vehicles	C	29	45
CX	Other manufacturing	C	12–18, 30–33	221
D	Energy supply	D except DX	all	30
DX	Biogas and solar plants	D	additionally defined	23
E	Water supply; wastewater and solid waste management & pollution cleanup	E	all	453
X	Other industries	A, F–U	all	912

* (Federal Statistical Office of Germany, 2008)

Table C.2: Industrial categorization

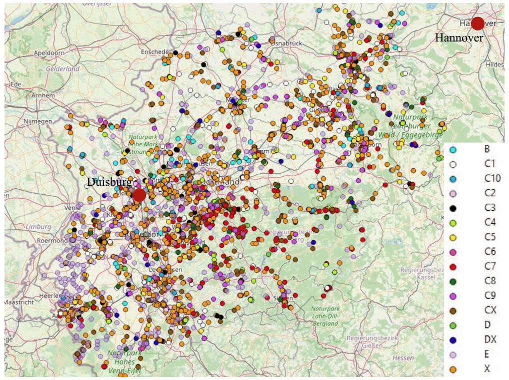

Figure C.3: Company locations by industry category

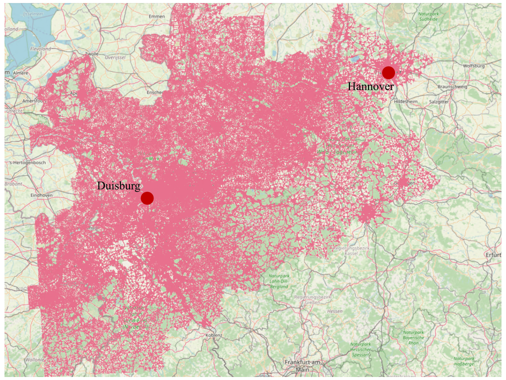

Figure C.4: Road network

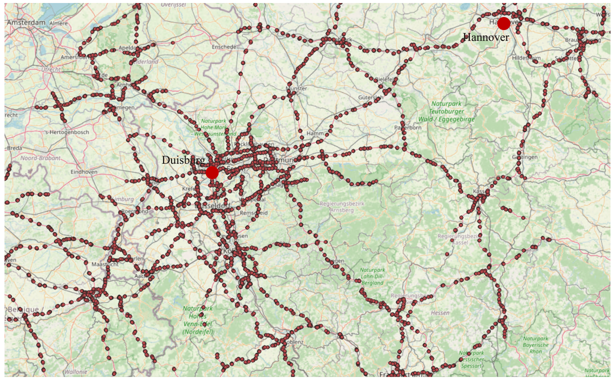

Figure C.5: Locations of the highway junctions

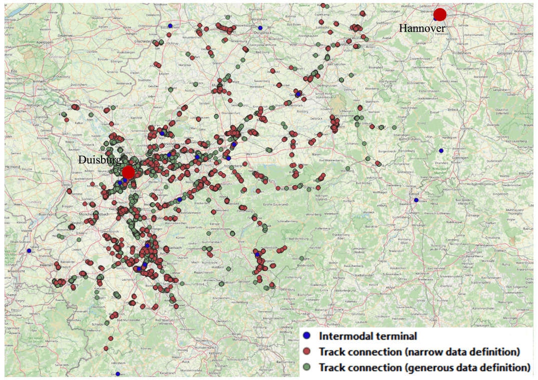

Figure C.6: Locations of the rail infrastructure

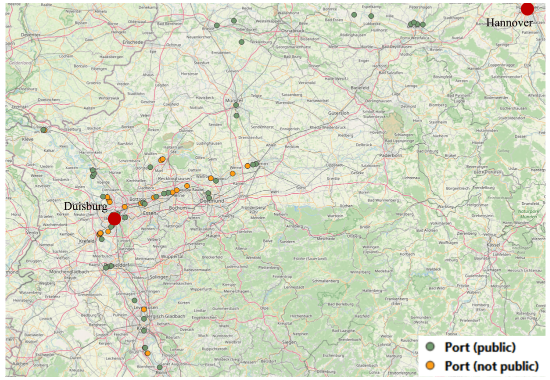

Figure C.7: Port locations

C.4.1.1.2 Step 3: Data analysis

The results of the application of Dijkstra's algorithm and an overview of the results of the radius analysis are given in Table C.3, showing for each industry category (1) the number of companies and (2) the percentage of companies that were assigned an AP.

The radius analysis is performed with radii of 250 meters and 500 meters for track connections and 2,000 meters for ports. The distance to the nearest AP is calculated for each industrial site, whereas an allocation is anticipated if this distance is less than the defined radius. Thus, for each industry, it is possible to determine the proportion of companies that have been assigned a track connection or a port. This result is taken as a measure of spatial proximity.

To optimize runtime, only the nearest APs are considered for each industrial site. Then, only the APs with the respective shortest travel times to each transport systems are considered. Furthermore, due to ambiguities in the extraction of rail APs from OSM, we used two different databases that included a more generous and narrower definition of track connections, respectively, as Table C.3 shows.

		Dijkstra				Radius analysis		
Industry category	**Number**	**Highway**	**Airport**	**Rail-road terminal**	**Public port**	**Port (not public)***	**Track connection (generous)***	**Track connection (narrow)***
B	44	9.17 min	45.37 min	25.27 min	22.20 min	4.55%	29.55%	15.91%
C1	137	8.77 min	42.29 min	29.38 min	30.68 min	0.73%	16.06%	6.57%
C2	15	6.52 min	35.58 min	13.03 min	8.95 min	53.33%	66.67%	33.33%
C3	61	7.15 min	41.05 min	24.94 min	22.57 min	13.11%	54.10%	29.51%
C4	80	12.45 min	51.23 min	33.40 min	40.86 min	1.25%	18.75%	7.50%
C5	118	10.26 min	40.89 min	32.92 min	36.32 min	2.54%	22.03%	13.56%
C6	59	7.19 min	42.18 min	22.72 min	26.32 min	8.47%	50.85%	20.34%
C7	325	9.36 min	52.35 min	30.48 min	39.86 min	1.54%	19.08%	11.69%
C8	106	10.06 min	48.95 min	31.76 min	34.53 min	0.94%	19.81%	14.15%
C9	238	8.57 min	44.70 min	28.04 min	33.70 min	0.84%	23.11%	9.66%
C10	45	8.02 min	40.21 min	30.12 min	36.02 min	0.00%	31.11%	22.22%
CX	221	10.21 min	47.21 min	33.37 min	36.56 min	0.90%	15.84%	10.41%
D	30	11.06 min	50.06 min	29.26 min	23.76 min	13.33%	56.67%	46.67%
DX	23	13.13 min	46.36 min	36.18 min	34.55 min	0.00%	8.70%	4.35%
E	423 (453)*	9.56 min	43.94 min	31.17 min	32.58 min	2.65%	11.92%	6.18%
X	898 (912)*	8.20 min	43.11 min	27.85 min	28.61 min	3.95%	28.84%	15.24%
All industries	2.823 (2.867)*	9.06 min	45.06 min	29.52 min	32.28 min	3.14%	23.44%	12.69%

* different numbers of industry E and X[2]

Table C.3: Averages of travel times (Dijkstra) and share of allocations (Radius analysis) by industry category

C.4.1.1.3 Step 4: Results and interpretation

The following values for the relative deviations[3] $d_{i,j}$ are proposed, in order to achieve five delimitable preference categories by applying Exp. C.1: $d_{1,2} = -0.15$, $d_{2,3} = -0.05$, $d_{3,4} = 0.05$, $d_{4,5} = 0.15$. A comprehensive analysis of all transport modes is performed to maximize knowledge gain and observe contradictions.

Figure C.8 visualizes the travel times to the highway interchanges, which are generally very short. The Pearson correlation coefficient between the industry mean values of travel times by modality and transport performance from freight statistics is $r = 0.280$ ($p = 0.433$; no significance). The preferences derived from the categorization hardly correspond to the importance of road transport for the respective industries, which can be seen in the freight statistics. Because of these inconsistencies, it is not possible to derive preferences for highway infrastructure from travel times.

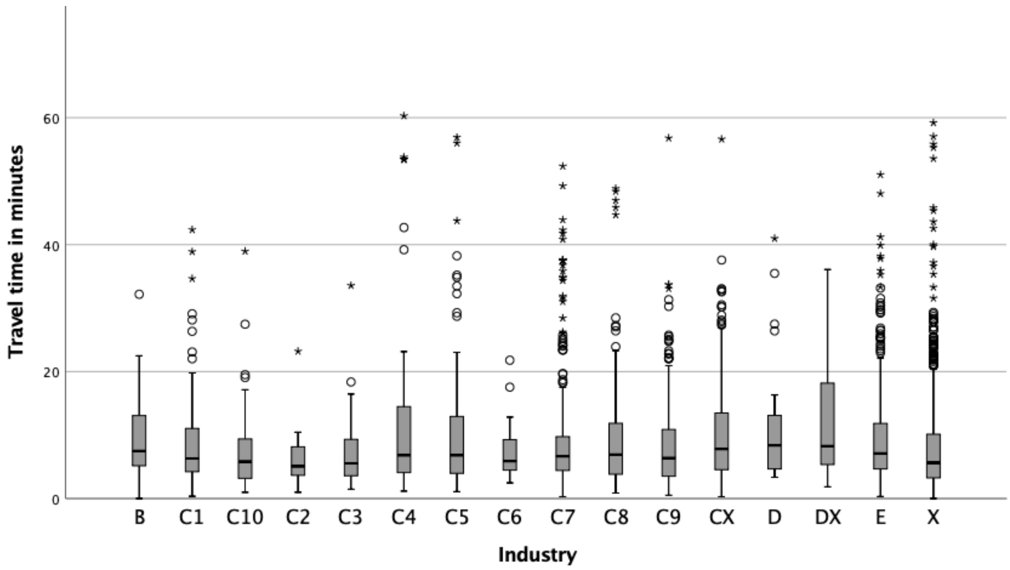

Figure C.8: Travel times to highway interchanges by industry category

Travel times to the nearest airport are shown in Figure C.9. We observe a wide range of data and no industry that has particularly short travel times. Since the freight statistics do not contain any data on air freight traffic, data on the export value of goods (German Aviation Association, 2017) is used for validation. Thereby, no significant preferences emerge, since the industries with the highest export value in air freight ("Electrotechnical goods", "Optical devices", "Machinery", "Pharmaceuticals and chemicals") do not have particularly short travel

[2] The OSM road data was used as LineString data and converted into a network with nodes and edges. Individual nodes could not be automatically connected to the network; hence, no route calculation was possible for individual companies. Due to the large sample, no manual post-recording was done for categories E and X, while companies in other categories with smaller data volumes were assigned manually. For the radius analysis, all companies could be considered, since its independence of road network data.

[3] Negative $d_{i,j}$ mean shorter travel times and higher preferences. The choice of values is based on observed distributions and sensitivity analyses of travel time deviations.

times to airports. Moreover, the industry with the shortest travel time has no significance in air freight transport according to statistics. Therefore, a derivation of preferences is not possible and no classification into preference categories is made.

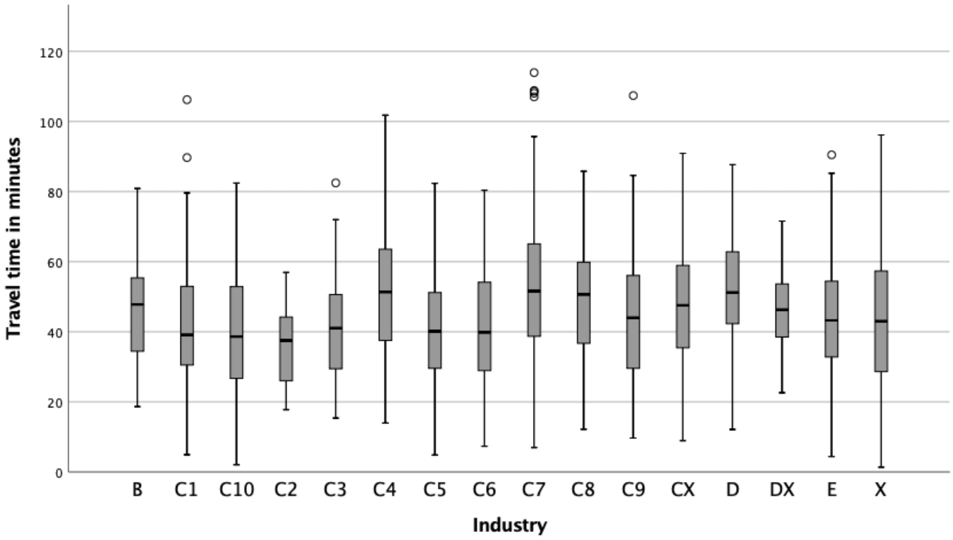

Figure C.9: Travel times to air freight locations by industry category

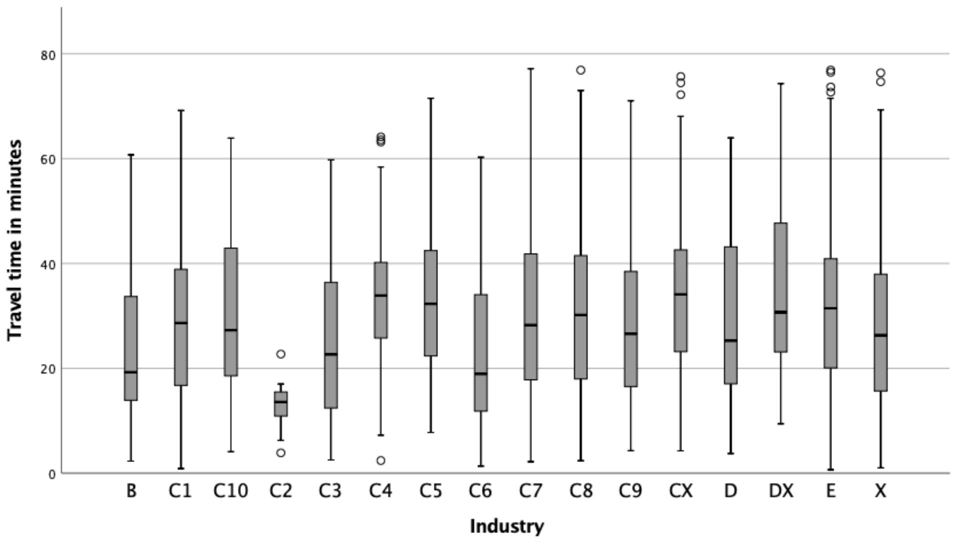

Figure C.10: Travel time to rail-road terminals by industry category

Figure C.10 shows the travel times to the rail-road terminals. The coking plant and mineral oil processing industry (C2) stands out with particularly short travel times. The correlation with freight statistics is negative at $r = -0.596$ ($p = 0.053$), but not statistically significant at the .05 level. Industries are then divided into preference categories (Table C.4).

Preference category	Assumed preference	Rail-road terminals		Public ports	
		Interval of the industry mean values of the travel times	Industry category	Interval of the industry mean values of the travel times	Industry category
1	Very large	[13.03 min; 25.09 min)	C2, C3, C6	[8.95 min; 27.44 min)	B, C2, C3, C6, D
2	Large	[25.09 min; 28.04 min)	B, X	[27.44 min; 30.67 min)	X
3	Average	[28.04 min; 31.00 min]	C1, C7, C9, C10, D	[30.67 min; 33.89 min]	C1, C9, E
4	Low	(31.00 min; 33.95 min]	C4, C5, C8, CX, E	(33.89 min; 37.12 min]	C5, C8, C10, CX, DX
5	Very low	(33.95 min; 36.18 min]	DX	(37.12 min; 40.86 min]	C4, C7

Table C.4: Preference categories and categorization of the industries

The fact that proximity to the rail infrastructure implies a higher preference is also observed when looking at the company's own track connections: The share of allocation is shown in dependence on the selected radius and the data basis in Figure C.11. Sectors with particularly high allocation shares also show significantly higher transport performance in the freight statistics.

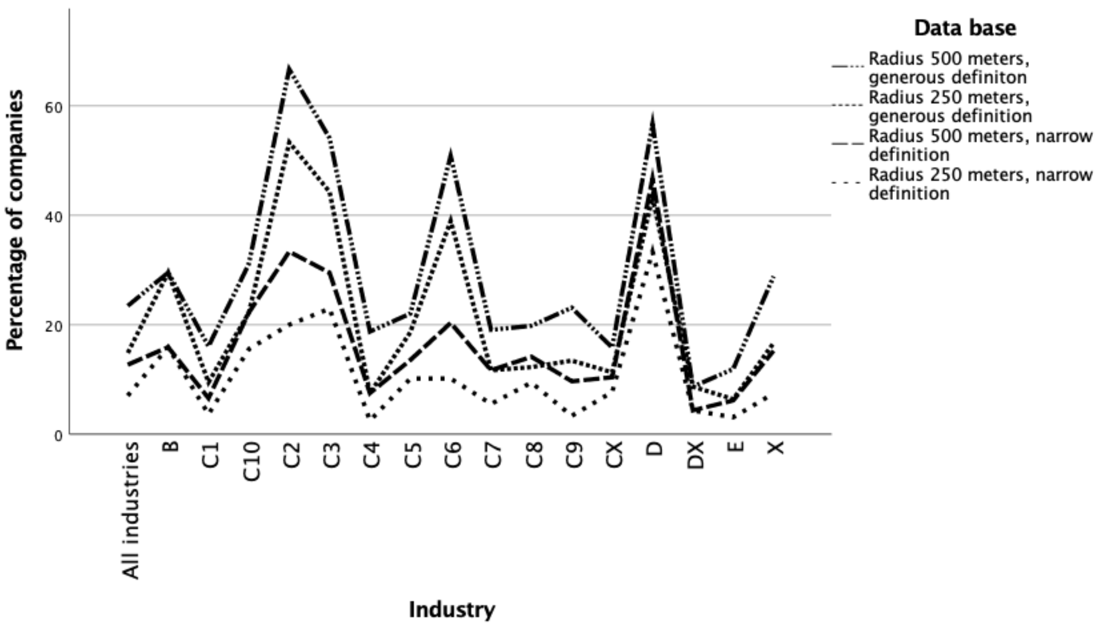

Figure C.11: Track connections: comparison of different parameters of radius analysis

Travel times to public ports are shown in Figure C.12. The correlation with freight statistics is strongly negative with $r = -0.862$ ($p = 0.001$). An overview of the correlations is given in Table C.5. Industries are also classified into preference categories for ports and identified preferences can be fully validated by the freight statistics (Table C.4). An examination of the allocation shares of non-public ports confirms this classification. The industries in the highest preference category also have the highest allocation shares and high transport performance in the freight statistics.

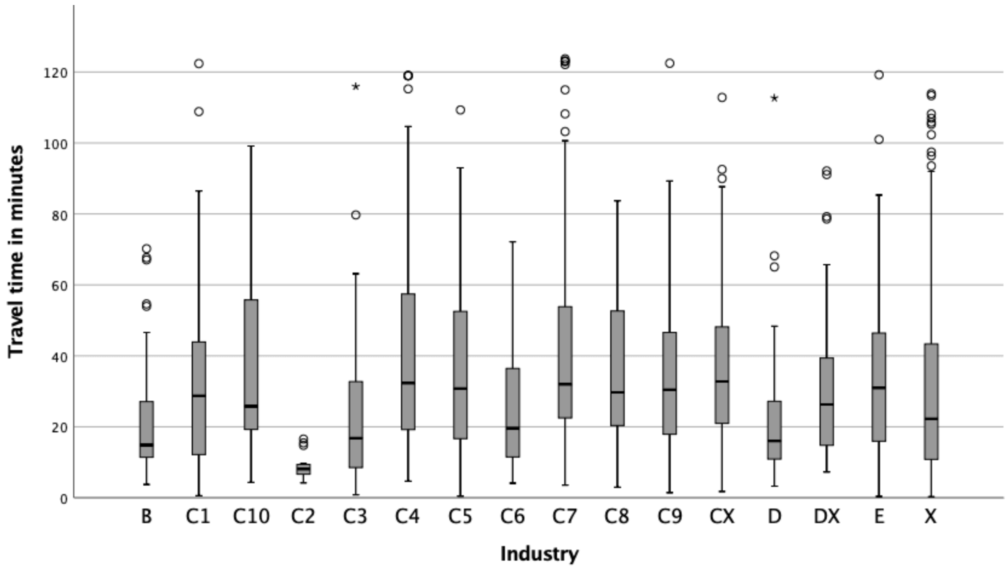

Figure C.12: Travel times to public ports by industry category

In summary, the proximity analysis only identified preferences for rail freight and freight shipping, but not for highway and air freight. The results show that the industries of mining and quarrying, coking plant and mineral oil processing (C2), production of chemical and pharmaceutical products (C3), metal production and processing (C6) and energy supply (D) show high preferences for rail freight transport and freight shipping. All other industries considered have only average or below average preferences for these two types of transport systems.

Thus, our sub-question *(1) Which industries and company-locations are directly affected by IWT failure?* can be answered on the basis of these location preferences. The affected industries and companies have the alternatives of relocating transports or entire sites if the function of IWT is restricted, which depends on the actual threat, the risk perception and the feasibility, economic efficiency and capacities of the alternatives.

	Parameters	Pearson correlation coefficient
Freight statistics	Highway junctions	r = 0.280 (p = 0.433)
	Rail-road terminals	r = -0.596 (p = 0.053)
	Public ports	r = -0.862 (p = 0.001)

Table C.5: Correlation coefficients of different transport systems

C.4.1.2 Empirical studies

The previous analysis supports the special role of IWT as mode of transport and allows to identify sectors and facility locations which are strongly dependent on IWT. Moreover, location preferences are derived. As these do not only depend on the accessibility to the infrastructure, but also on the availability and the resulting risk perception and business activities play an important role, a deeper analysis of these factors and interdependencies is conducted based on the elaborations in Section C.3.2.2 and the results of the previous section.

C.4.1.2.1 Step 1: Key question and Hypotheses

The two key questions are formulated in Section C.3.2.2, leading to eight significant research topics which are depicted in Table C.6 and serve as the basis for the hypotheses, two of which are shown in Table C.7.

Nr.	Research topic
R1	Flow of goods and supply relationships
R2	Temporal disturbance progressions
R3	Vulnerabilities of various industries
R4	Application of risk reduction measures
R5	Assessment of damage caused by interrupted supply chains
R6	Identification of highly critical event scenarios
R7	Effect of water contamination and shortage of cooling water
R8	Connections with other CI: power supply and water supply

Table C.6: Research topics

Nr.	Research topic	Hypothesis
H1	R1, R4	For transports currently transported via waterways, there are hardly any alternative options
H2	R2, R5	It is feared that dependence on IWT will lead to considerable problems in the future

Table C.7: Hypotheses

C.4.1.2.2 Step 2: Survey

In the first instance, an online questionnaire consisting of qualitative and quantitative, mostly closed questions was conducted to address the hypotheses, as can be seen from the entire questionnaire as appendix. Thereby, the pattern of industries to which the recipients belonged to was quite heterogeneous except the commonality that the represented firms are dependent on

IWT. Primarily, entrepreneurs located in the area of NRW were contacted. Thus, a total of 231 companies and associations were contacted, with a response rate of only 21 usable responses[4].

To assess the vulnerability of industrial facilities, company representatives were asked about the measures companies are already taking to reduce risks from waterway dependency. In this context, more than 60% rely on a shift of transport mode, as Figure C.13 shows. Measures of expanding storage capacity as well as the use of a redundant water supply are pointed out by a much lower percentage of companies. The latter is due to the fact that water extraction from the canal network is not carried out by many companies and is not further relevant to the transport aspect of H1.

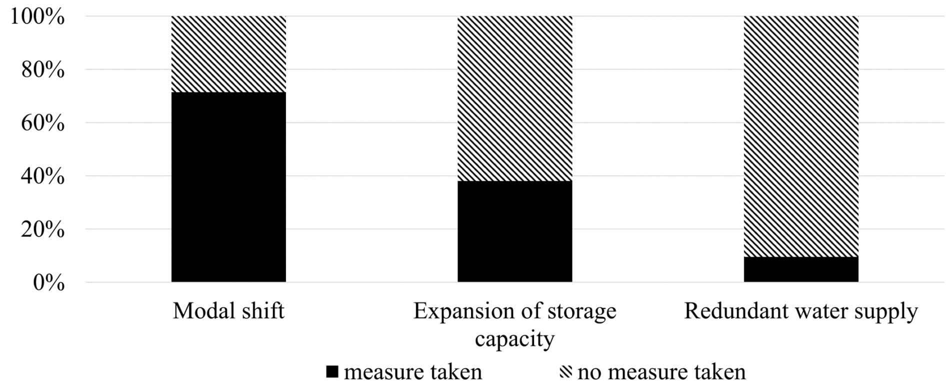

Figure C.13: Measures to reduce risks arising from waterways

Moreover, if the measure of modal shift is considered, the following can be observed: Participants that have implemented modal shift measures in the past are more likely to have planned to do so in the future. According to an adjusted t-test (Welch test), the likelihood of shifting traffic in the future was found to be 80% higher among those who are currently already doing so than among those who are not currently implementing any modal shift measures.

A closer look at modal shift reveals that, according to the companies' assessment, the short-term shift to road has the largest potential for modal shift, with a medium rating of 40%. Rail plays only a minor role and is hardly available in the short term, as depicted in Figure C.14.

4 25 responses, removal of 4 due to duplicate records or non-relevance for IWT.

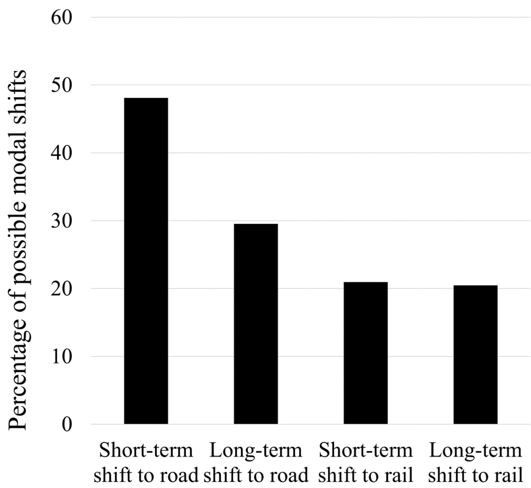

Figure C.14: Extent of possible modal shift

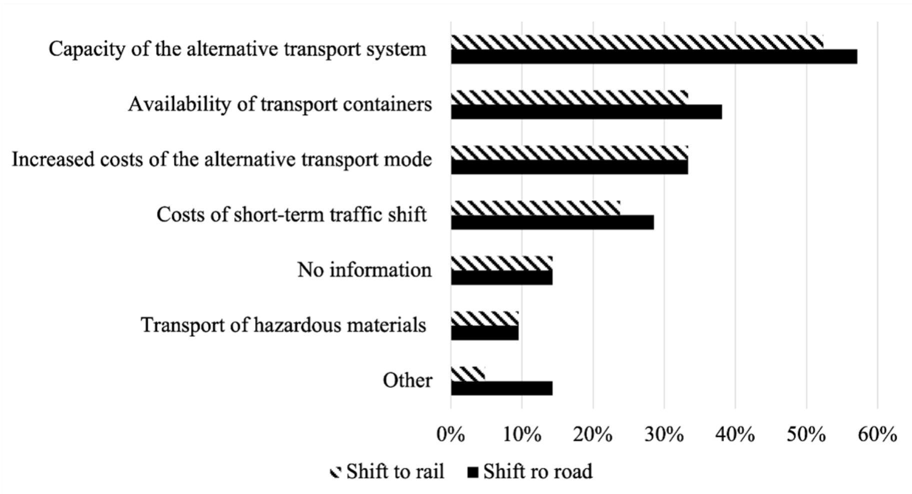

Figure C.15: Barriers to modal shift

The barriers to modal shift (Figure C.15) furthermore reveal that the capacity of alternative transport systems as well as increased costs are significant factors that stand in the way of modal shift. This is equally true for rail and road, with barriers to modal shift to rail considered to be higher.

Consequently, transport that currently takes place via waterways is indeed difficult to shift, especially since the focus of the surveyed firms lied mostly on alternative short-term options and the barriers for a long-term shift of transport were perceived as too high.

Moreover, company representatives were asked to rate, how much of an impact a 3-week shutdown would have on business operations. The results, illustrated by Figure C.16, show that the longer the lead time, the less constrained companies' ability to do business. With a warning period of one month, no severe problem is initially feared. In contrast, a warning period of only one day leads to a much higher impairment of business activity.

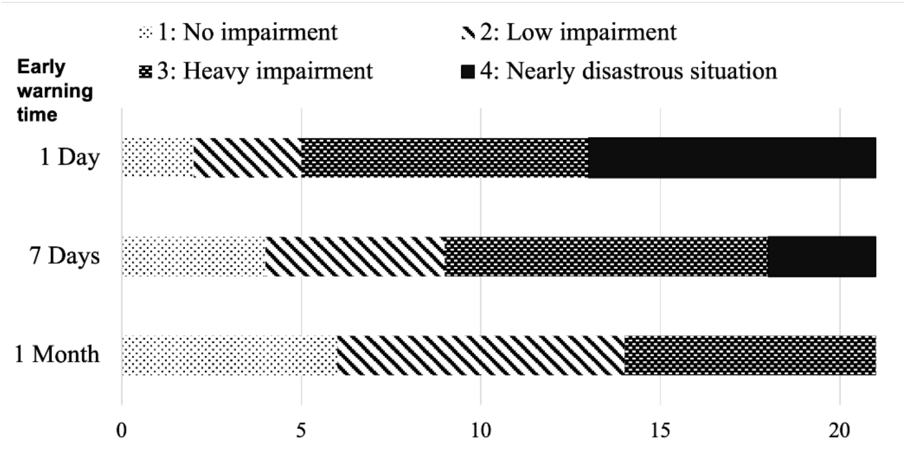

Figure C.16: Criticality depending on early warning time – closure of three weeks

An examination of the correlation (Figure C.17) with revenue also shows that the higher the company's revenue, the higher the level of constraint as the lead time becomes shorter. Reasons for this could be the more complex infrastructures and processes as well as higher flows of goods that larger companies have to convert. They can often only act much less flexibly than smaller companies.

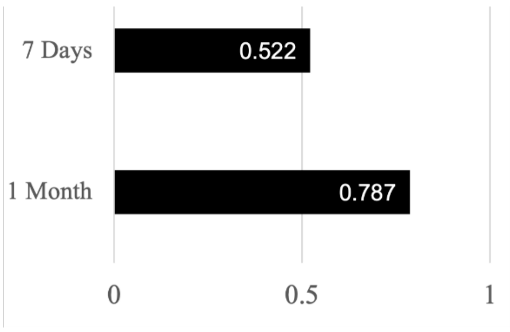

Figure C.17: Correlation r with annual turnover

Thus, regarding our hypotheses, H1 could be confirmed. In contrast, H2 could not be confirmed because risk on current and future maintenance of the canal system was rated mostly the same over the considered companies, as Figure C.18 shows.

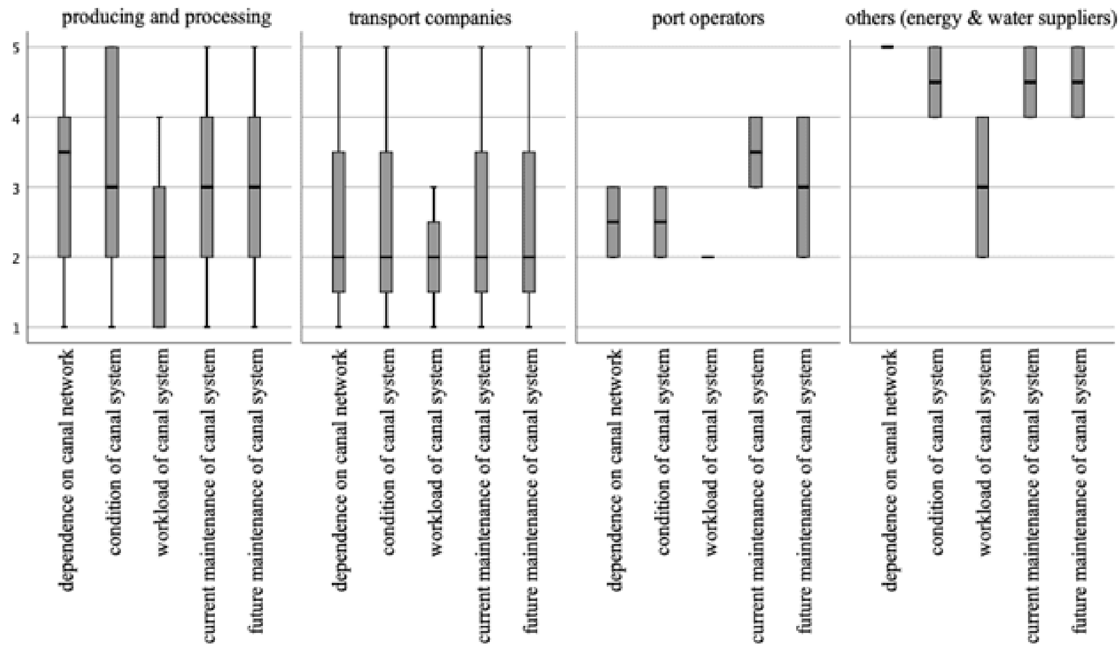

Figure C.18: Risk perception depending on type of company

C.4.1.2.3 Step 3: Expert interviews

To gather more detailed background information two interviews were conducted in accordance with hypotheses and the online questionnaire. Participants were asked about the following topics: the company's dependence on the waterway, the company's perception of risk, the measures required in relation to the IWT.

The questions examined at what point in time closures threaten to severely disrupt company's business operations and whether this impairment can be avoided or greatly reduced by a sufficiently long warning period. The responses provide an understanding of the background of the survey data. Moreover, we could also gain deeper insights into a central aspect of H2: Maintenance today is inadequate with a backlog of modernization and the situation is expected to worsen due to increasing aging. However, the answers also indicate hope reflected by planned measures as shown by Figure C.18.

The selected modelling region causes a limitation for the analysis of companies in NRW, with OpenStreetMap (OSM) being the main source for data collection. APs are highway interchanges as APs to the road network, rail-road terminals as APs to the rail network, ports as APs to IWT, and airports as APs to air transport. For the rail and waterway networks, a distinction is made between whether an AP is public or own-use company property.

C.4.1.2.4 Step 4: Combined results

We now turn to the relationship between IWT-preference and criticality, which we find to be positively correlated. Our results are significant at an early warning time of 7 days (r $= 0.682$) and of 1 month (r $= 0.743$). The IWT-preferences are derived from the proximity analysis and show high preference levels and thus the correlated high criticality for the sectors mining and quarrying, coking plant and mineral oil processing, production of chemical and pharmaceutical products, metal production and processing and energy supply. To answer our research question *(2) What business decisions may result from lasting availability reductions of IWT?* , we proceed with a combined evaluation and get the following findings:

- Early warning time is of high importance for firms to be able to react to restrictions of IWT,
- infrastructure disruptions hit firms especially hard due to a lack of road and rail capacities and
- whether the negative effects of a reduced infrastructure availability can be considerably reduced by sufficient early warning time depends on the vulnerability of the company.

C.5 Summary, discussion and conclusions

In this contribution, we carried out a risk assessment of the waterway infrastructure as a barely studied transport system. We analyzed risk exposure stemming from infrastructure failure and had a focal look at economic effects on potentially affected industries. From a methodological point of view, we used GIS-Analyses, economic statistics, and industry surveys which we applied to the case of NRW.

Analytical insights include substantial qualitative and quantitative impacts on industry and population that arise if waterways are not maintained. In detail, our elaborations on the economic risk potential show the significance of vulnerability and criticality of industrial sectors and a predominance of location preferences for several industrial sectors. Non-existent or not usable capacities of alternative modes of transport pose a threat to business locations if the condition of waterways deteriorates significantly. The proximity analysis therefore provides an overview of affected facilities in case of disruptive events, while empirical studies contribute to the understanding of company decisions as reaction on actual and perceived risk arising from the dependence of IWT.

Thereby, these results are of high interest for stakeholders from industry, since they are enabled to assess the resilience of their business locations and SCs when considering our survey. Thus, those responsible from both infrastructure and industry should work together to enhance and preserve business locations. To apply effective holistic risk-avoiding and risk-preventing measures in the long-term, further research should also consider other external incentives for location-relocation mechanisms and their interaction with the observed factor of infrastructure availability.

The incorporation of empirical data and expert's knowledge into the development of a risk-based maintenance strategy should be pursued further, while an extension of the economic risk potential analysis by an extension of the provided survey toward further companies can be aimed. This could allow a more specific analysis and may refine possible gradations of risk and maintenance prioritization. Nevertheless, given the usual difficulties of data collection on a regional and local basis, we already extracted large amounts of regional and specific data to employ them for our analyses.

Acknowledgments

The authors want to thank the partners in the joint research project for Digital and Transport (2018). The project is funded by the security research program (www.sifo.de) of the German Federal Ministry of Education and Research (BMBF; grant number 13N14697). Special thanks go to the participants of the survey, who shared their expertise, thereby supporting this research.

References

Arunotayanun, K., Polak, J. W. (2011). Taste Heterogeneity and Market Segmentation in Freight Shippers' Mode Choice Behaviour. *Transportation Research Part E: Logistics and Transportation Review*, *47*(2), 138–148.

Bernacki, D., Lis, C. (2021). Investigating the Sustainable Impact of Seaport Infrastructure Provision on Maritime Component of Supply Chain. *Energies*, *14*(12), 3519.

Bierwirth, C., Kirschstein, T., Meisel, F. (2012). On Transport Service Selection in Intermodal Rail/Road Distribution Networks. *Business Research*, *5*(2), 198–219.

Bolis, S., Maggi, R. (2003). Logistics Strategy and Transport Service Choices: An Adaptive Stated Preference Experiment. *Growth and Change*, *34*(4), 490–504.

Boloori Arabani, A., Farahani, R. Z. (2012). Facility Location Dynamics: An Overview of Classifications and Applications. *Computers & Industrial Engineering*, *62*(1), 408–420.

Buldyrev, S. V., Parshani, R., Paul, G., Stanley, H. E., Havlin, S. (2010). Catastrophic Cascade of Failures in Interdependent Networks. *Nature*, *464*, 1025–1028.

Button, K. J., Leitham, S., McQuaid, R. W., Nelson, J. D. (1995). Transport and Industrial and Commercial Location. *The Annals of Regional Science*, *29*(2), 189–206.

Carboni, O. A. (2013). Spatial and Industry Proximity in Collaborative Research: Evidence from Italian Manufacturing Firms. *The Journal of Technology Transfer*, *38*(6), 896–910.

Chopra, S., Meindl, P. (2007). *Supply Chain Management: Strategy, Planning, and Operation* (3rd ed.). Upper Saddle River, NJ: Pearson/Prentice Hall.

Coetzee, P., Swanepoel, P. A. (2017). Spatial Relationships and Movement Patterns of the Air Cargo Industry in Airport Regions. *Journal of Transport and Supply Chain Management*, *11*(0), 10.

Craighead, C. W., Blackhurst, J., Rungtusanatham, M. J., Handfield, R. B. (2007). The Severity of Supply Chain Disruptions: Design Characteristics and Mitigation Capabilities. *Decision Sciences*, *38*(1), 131–156.

Cui, T., Ouyang, Y., Shen, Z.-J. M. (2010). Reliable Facility Location Design Under the Risk of Disruptions. *Operations Research*, *58*(4-part-1), 998–1011.

de Bok, M. (2009). Estimation and Validation of a Microscopic Model for Spatial Economic Effects of Transport Infrastructure. *Transportation Research Part A: Policy and Practice*, *43*(1), 44–59.

de Bok, M., Sanders, F. (2005). Firm Relocation and Accessibility of Locations. *Transportation Research Record: Journal of the Transportation Research Board*, *1902*(1), 35–43.

de Bok, M., van Oort, F. (2011). Agglomeration Economies, Accessibility and the Spatial Choice Behavior of Relocating Firms. *Journal of Transport and Land Use*, *4*(1), 5.

Deng, T. (2013). Impacts of Transport Infrastructure on Productivity and Economic Growth: Recent Advances and Research Challenges. *Transport Reviews*, *33*(6), 686–699.

Deutsche Umschlaggesellschaft Schiene - Straße (DUSS) mbH (Ed.). (2017). *DUSS-Terminals*. Retrieved 10.06.2020, from http://www1.deutschebahn.com/ecm2-duss/terminals_uebersicht

Dubé, J., Thériault, M., Des Rosiers, F. (2013). Commuter Rail Accessibility and House Values: The Case of the Montreal South Shore, Canada, 1992–2009. *Transportation Research Part A: Policy and Practice*, *54*(6), 49–66.

Eberts, R. W., McMillen, D. P. (1999). Applied Urban Economics, Chapter 38 Agglomeration Economies and Urban Public Infrastructure. In (Vol. 3, pp. 1455–1495). Elsevier.

Efthymiou, D., Antoniou, C. (2013). How do Transport Infrastructure and Policies Affect House Prices and Rents? Evidence from Athens, Greece. *Transportation Research Part A: Policy and Practice*, *52*(1), 1–22.

Elliott, V., Theodoulou, M. (2004). *Merry Christmas, your PlayStation 2 is stuck in Suez*. The Times. Retrieved 01.25.2022, from http://www.thetimes.co.uk/article/merry-christmas-your-playstation-2-is-stuck-in-suez-5l8j7g2wrtm

Farahani, R. Z., Drezner, Z., Asgari, N. (2009). Single Facility Location and Relocation Problem with Time Dependent Weights and Discrete Planning Horizon. *Annals of Operations Research*, *167*(1), 353–368.

Federal Ministry for Digital and Transport (Ed.). (2015). Verkehrsinfrastrukturbericht.

Federal Ministry for Digital and Transport (Ed.). (2019). Masterplan Binnenschifffahrt.

Federal Ministry of the Interior and Community (Ed.). (2011). Schutz Kritischer Infrastrukturen – Risiko- und Krisenmanagement: Leitfaden für Unternehmen und Behörden.

Federal Statistical Office of Germany (Ed.). (2008). *Klassifikation der Wirtschaftszweige*. Retrieved 02.06.2020, from http://www.destatis.de/static/DE/dokumente/klassifikation-wz-2008-3100100089004.pdf

Federal Statistical Office of Germany (Ed.). (2019). Verkehr: Güterverkehrsstatistik der Binnenschifffahrt. , *4*(8).

Federal Waterways and Shipping Agency of Germany (Ed.). (2014). *Verkehrsbericht 2013 Niederrhein und westdeutsches Kanalnetz*. Retrieved from http://henry.baw.de/handle/20.500.11970/105054?show=full

Fekete, A. (2011). Common Criteria for the Assessment of Critical Infrastructures. *International Journal of Disaster Risk Science*, *2*(1), 15–24.

for Digital, F. M., Transport. (2018). *Verbundforschungsvorhaben Resilienz kritischer Verkehrsinfrastrukturen am Beispiel der Wasserstraßen.* Retrieved from https://www.sifo.de/sifo/de/projekte/schutz-kritischer-infrastrukturen/verkehrsinfrastrukturen/preview-resilienz-kritischer-v-am-beispiel-der-wasserstrassen/preview-resilienz-kritischer-v-am-beispiel-der-wasserstrassen.html

Fujimoto, T. (2011). *Supply Chain Competitiveness and Robustness: A Lesson from the 2011 Tohoku Earthquake and Supply Chain "Virtual Dualization".*

García-Menéndez, L., Martínez-Zarzoso, I., Miguel, D. P. D. (2004). Determinants of Mode Choice between Road and Shipping for Freight Transport: Evidence for Four Spanish Exporting Sectors. *Journal of Transport Economics and Policy*, *38*(3), 447–466.

Geofabrik GmbH (Ed.). (2020). *Europe.* Retrieved 03.03.2020, from http://download.geofabrik.de/europe.html

German Aviation Association (Ed.). (2017). *Was wird per Luftfracht transportiert?* Retrieved 11.07.2020, from http://www.bdl.aero/de/publikation/was-wird-per-luftfracht-transportiert/

Graham, D. J. (2007). Agglomeration, Productivity and Transport Investment. *Journal of Transport Economics and Policy*, *41*(3), 317–343.

Haraguchi, M., Lall, U. (2015). Flood Risks and Impacts: A Case Study of Thailand's Floods in 2011 and Research Questions for Supply Chain Decision Making. *International Journal of Disaster Risk Reduction*, *14*, 256–272.

Holl, A. (2004). Manufacturing Location and Impacts of Road Transport Infrastructure: Empirical Evidence from Spain. *Regional Science and Urban Economics*, *34*(3), 341–363.

Hosseini, S., Barker, K. (2016). Modeling Infrastructure Resilience using Bayesian Networks: A Case Study of Inland Waterway Ports. *Computers & Industrial Engineering*, *93*(7), 252–266.

Hulten, C. R., Bennathan, E., Srinivasan, S. (2006). Infrastructure, Externalities, and Economic Development: A Study of the Indian Manufacturing Industry. *The World Bank Economic Review*, *20*(2), 291–308.

Huth, M., Romeike, F. (Eds.). (2016). *Risikomanagement in der Logistik: Konzepte - Instrumente - Anwendungsbeispiele* (1st ed.). Wiesbaden: Springer Gabler.

Ivanov, D., Dolgui, A. (2019). Low-Certainty-Need (LCN) Supply Chains: A New Perspective in Managing Disruption Risks and Resilience. *International Journal of Production Research*, *57*(15-16), 5119–5136.

Janic, M. (2000). An Assessment of Risk and Safety in Civil Aviation. *Journal of Air Transport Management*, *6*(1), 43–50.

Jin, F., Wang, C., Li, X., Wang, J. (2010). China's Regional Transport Dominance: Density, Proximity, and Accessibility. *Journal of Geographical Sciences*, *20*(2), 295–309.

Jüttner, U., Peck, H., Christopher, M. (2003). Supply Chain Risk Management: Outlining an Agenda for Future Research. *International Journal of Logistics Research and Applications*, *6*(4), 197–210.

Khan, O., Burnes, B. (2007). Risk and Supply Chain Management: Creating a Research Agenda. *The International Journal of Logistics Management*, *18*(2), 197–216.

Knowles, R. D., Ferbrache, F. (2016). Evaluation of Wider Economic Impacts of Light Rail Investment on Cities. *Journal of Transport Geography*, *54*(4), 430–439.

Kotowska, I., Mańkowska, M., Pluciński, M. (2018). Inland Shipping to Serve the Hinterland: The Challenge for Seaport Authorities. *Sustainability*, *10*(10), 3468.

Larocco, L. A. (2021). *Suez Canal Blockage is Delaying an Estimated $400 Million an Hour in Goods*. CNBC. Retrieved 01.25.2022, from http://www.cnbc.com/2021/03/25/suez-canal-blockage-is-delaying-an-estimated-400-million-an-hour-in-goods.html

Lenz, S. (2009). *Vulnerabilität kritischer Infrastrukturen.*

Lim, M. K., Bassamboo, A., Chopra, S., Daskin, M. S. (2013). Facility Location Decisions with Random Disruptions and Imperfect Estimation. *Manufacturing & Service Operations Management*, *15*(2), 239–249.

Lücker, F., Seifert, R. W., Biçer, I. (2019). Roles of Inventory and Reserve Capacity in Mitigating Supply Chain Disruption Risk. *International Journal of Production Research*, *57*(4), 1238–1249.

Malmberg, A., Maskell, P. (1997). Towards an Explanation of Regional Specialization and Industry Agglomeration. *European Planning Studies*, *5*(1), 25–41.

McCalla, R. J., Slack, B., Comtois, C. (2001). Intermodal Freight Terminals: Locality and Industrial Linkages. *The Canadian Geographer/Le Géographe canadien*, *45*(3), 404–413.

Meixell, M. J., Norbis, M. (2008). A Review of the Transportation Mode Choice and Carrier Selection Literature. *The International Journal of Logistics Management*.

Mejia-Dorantes, L., Paez, A., Vassallo, J. M. (2012). Transportation Infrastructure Impacts on Firm Location: The Effect of a New Metro Line in the Suburbs of Madrid. *Journal of Transport Geography*, *22*, 236–250.

Mulley, C., Ma, L., Clifton, G., Yen, B., Burke, M. (2016). Residential Property Value Impacts of Proximity to Transport Infrastructure: An Investigation of Bus Rapid transit and heavy rail networks in brisbane, australia.

New Zealand Ministry of Foreign Affairs and Trade (Ed.). (2021). *The Importance of the Suez Canal to Global Trade - 18 April 2021*. Retrieved 01.25.2022, from http://www.mfat.govt.nz/de/trade/mfat-market-reports/market-reports-middle-east/the-importance-of-the-suez-canal-to-global-trade-18-april-2021/

Novotný, P., Markuci, J., Titko, M., Slivková, S., Řehák, D. (2015). Practical Application Of A Model For Assessing The Criticality Of Railway Infrastructure Elements. *TRANSACTIONS of the VŠB – Technical University of Ostrava, Safety Engineering Series*, *10*(2), 26–32.

OpenStreetMap Foundation (Ed.). (2019). *DE:Overpass API.* Retrieved 20.05.2020, from http://wiki.openstreetmap.org/wiki/DE:Overpass_API

Oum, T. (1979). A Cross Sectional Study of Freight Transport Demand and Rail-Truck Competition in Canada.

Owen, S. H., Daskin, M. S. (1998). Strategic Facility Location: A Review. *European Journal of Operational Research*, *111*(3), 423–447.

Oztanriseven, F., Nachtmann, H. (2020). Modeling Dynamic Behavior of Navigable Inland Waterways. *Maritime Economics & Logistics*, *22*(2), 173–195.

Park, Y., Hong, P., Roh, J. J. (2013). Supply Chain Lessons from the Catastrophic Natural Disaster in Japan. *Business Horizons*, *56*(1), 75–85.

Ranieri, L., Digiesi, S., Silvestri, B., Roccotelli, M. (2018). A Review of Last Mile Logistics Innovations in an Externalities Cost Reduction Vision. *Sustainability*, *10*(3), 782.

Rezaei, J., van Roekel, W. S., Tavasszy, L. (2018). Measuring the Relative Importance of the Logistics Performance Index Indicators using Best Worst Method. *Transport Policy*, *68*, 158–169.

Rinaldi, S. M., Peerenboom, J., Kelly, T. K. (2001). Identifying, Understanding, and Analyzing Critical Infrastructure Interdependencies. *IEEE Control Systems*, *21*(6), 11–25.

Rohács, J., Simongáti, G. (2007). The Role of Inland Waterway Navigation in a Sustainable Transport System. *Transport*, *22*(3), 148–153.

Santos, G., Behrendt, H., Maconi, L., Shirvani, T., Teytelboym, A. (2010). Part I: Externalities and Economic Policies in Road Transport. *Research in Transportation Economics*, *28*(1), 2–45.

Shukla, V., Waddell, P. (1991). Firm Location and Land use in Discrete Urban Space: A Study of the Spatial Structure of Dallas-Fort Worth 0. *Regional Science and Urban Economics*, *21*(2), 225–253.

Snyder, L. V., Atan, Z., Peng, P., Rong, Y., Schmitt, A. J., Sinsoysal, B. (2016). OR/MS Models for Supply Chain Disruptions: A Review. *IIE Transactions*, *48*(2), 89–109.

Snyder, L. V., Daskin, M. S. (2005). Reliability Models for Facility Location: The Expected Failure Cost Case. *Transportation Science*, *39*(3), 400–416.

SteadieSeifi, M., Dellaert, N. P., Nuijten, W., van Woensel, T., Raoufi, R. (2014). Multimodal Freight Transportation Planning: A Literature Review. *European Journal of Operational Research*, *233*(1), 1–15.

Theoharidou, M., Kotzanikolaou, P., Gritzalis, D. (2009). Risk-Based Criticality Analysis. In C. Palmer S. Shenoi (Eds.), *Critical Infrastructure Protection III* (pp. 35–49). Berlin, Heidelberg: Springer Berlin Heidelberg.

Thomas, I., .Hermia, J., Vanelslander, T., Verhetsel, A. (2003). Accessibility to freight transport networks in belgium: A geographical approach.

Ukkusuri, S. V., Yushimito, W. F. (2009). A Methodology to Assess the Criticality of Highway Transportation Networks. *Journal of Transportation Security*, *2*(1), 29–46.

Utne, I. B., Hokstad, P., Vatn, J. (2011). A Method for Risk Modeling of Interdependencies in Critical Infrastructures. *Reliability Engineering & System Safety*, *96*(6), 671–678.

Vedovello, C. (1997). Science Parks and University-Industry Interaction: Geographical Proximity Between the Agents as a Driving Force. *Technovation*, *17*(9), 491–531.

Vierth, I., Merkel, A. (2020). Internalization of External and Infrastructure Costs Related to Maritime Transport in Sweden. *Research in Transportation Business & Management*, *58*(1), 100580.

Wang, S.-L., Schonfeld, P. (2005). Scheduling Interdependent Waterway Projects through Simulation and Genetic Optimization. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, *131*(3), 89–97.

Wehrle, R., Wiens, M., Neff, F., Schultmann, F. (2022). Economic risk potential of infrastructure failure considering inland waterways.

Wehrle, R., Wiens, M., Schultmann, F., Akkermann, J., Bödefeld, J. (2020). Ebenensystem zur Resilienzbewertung kritischer Verkehrsinfrastrukturen am Beispiel der Wasserstraßen. *Bautechnik*, *97*(6), 395–403.

WSA Westdeutsche Kanäle (Ed.). (2022). *Wasserstraßen des WSA*. Retrieved 05.01.2022, from http://www.wsa-westdeutsche-kanaele.wsv.de/Webs/WSA/Westdeutsche-Kanaele/DE/Wasserstrassen/wasserstrassen_node.html

Wu, T., Blackhurst, J., O'grady, P. (2007). Methodology for Supply Chain Disruption Analysis. *International Journal of Production Research*, *45*(7), 1665–1682.

Yu, H., Zeng, A. Z., Zhao, L. (2009). Single or Dual Sourcing: Decision-Making in the Presence of Supply Chain Disruption Risks. *Omega*, *37*(4), 788–800.

Zotti, J., Danielis, R. (2004). Freight Transport Demand in the Mechanical Sector of Friuli Venezia Giulia: The Choice Between Intermodal and road transport.

Zsidisin, G. A. (2003). A Grounded Definition of Supply Risk. *Journal of Purchasing and Supply Management*, *9*(5-6), 217–224.

D On the influence of infrastructure availability on companies decisions towards modal shift and relocation of facilities

Abstract[1]

Purpose - Manufacturing companies and their global supply chains are highly dependent on the availability of transport infrastructures. This paper evaluates companies' business decisions in reaction to availability reductions of inland waterway transport (IWT). Reduced infrastructure availability may lead to modal shifts in the short term but can also lead to relocation decisions of whole facilities.
Methodology - A scenario-based transport model evaluates increasing transport costs due to availability reductions of infrastructure. The results are used to assess the probability of relocating facilities by deriving their benefit from infrastructure condition.
Findings - The study identifies critical thresholds for infrastructure availability and analyzes business decisions in the context of maintaining public infrastructure to sustain local industries and to maintain business locations.
Research limitations - The case focuses on the specific area of inland waterways and highly dependent sectors on this infrastructure.
Practical implications - Public authorities should consider the effect of their infrastructure investment decisions on local areas' attractiveness as business location. The paper provides insight into the decisive consequences of companies' decisions and raises awareness of the relevance of infrastructure investments.
Originality - The paper connects the concepts of short-term agility and long-term resilience with companies' decisions and exogenous factors such as infrastructure availability. The applied use case focuses on a barely studied type of infrastructure that will gain in importance in light of sustainability and climate change.

---

[1] This chapter includes the preprint of the article "On the influence of infrastructure availability on companies decisions towards modal shift and relocation of facilities" by Johannes Gast, Marcus Wiens, Frank Schultmann, and myself (Wehrle, Gast, et al., 2022).

Keywords: Relocation; Infrastructure maintenance; Transport; FLP; Resilience; SCM

D.1 Introduction

Global Supply Chains (SCs) aim to reap the synergies of production costs and transportation costs as keenly as possible for given service and quality target levels. They enable the production of low-value products at high volume due to economies of scale (Doorly, 2020). However, the rising importance of sustainability calls for the emerging trend of de-globalization, which aims to tie back SCs to their local sales market in order to reduce environmental impacts (Helm, 2020), among others. Furthermore, globalized SCs lead to complex SC networks that are vulnerable to disruptions due to their inherent complex and global interdependencies (Doorly, 2020).

SC disruptions imply the combination of an unanticipated event and the resulting consequences, which significantly endanger the flow of materials and normal business activities (Bugert and Lasch, 2018; Faertes, 2015; Wagner and Bode, 2006). In a world of increasing risks (World Economic Forum, 2021), the threat of escalating SC disruptions endangers economic welfare, which moreover exerts pressure in the direction of de-globalization, too. Countering these threats requires shifts of several factors in international business (Witt, 2019). Enhancing SC resilience and SC viability can prevent these disruptions and their resulting negative impacts(Ivanov, 2020; Hosseini et al., 2019). Overall, enhanced resilience could support the domestic business activities at a company's location, whereas an ensured access to available transportation infrastructure is one of the most important factors for manufacturing business locations (Mejia-Dorantes et al., 2012; Rezaei et al., 2018).

As a key resilience strategy, companies make investments into improved flexibility of their own SC network to strengthen the reliability of their operations, thus preventing losses from external and internal disruptions (Choi, 2021; Tomlin, 2006). However, such investment decisions require an in-depth assessment of external factors that affect SC flexibility, which is not within the company's decision-making scope (Braunscheidel and Suresh, 2009; Brusset and Teller, 2017). One of the most important external factors in the context of SCs is the availability of transport infrastructure, the planning and maintenance of which regularly lies in the public sector (Essen et al., 2020). Hence, in most countries, the state is responsible for maintaining a sufficient level of infrastructure availability (Li et al., 2019). Therefore, public investments in the maintenance and expansion of public infrastructure play a central and still underestimated role.

For companies, this externality constitutes a dilemma: Although their operations depend on the permanent availability of public infrastructure, they have neither direct influence on maintenance or expansion decisions nor can they ensure timely transmission of information about short-time availability and status of transportation infrastructure.

Since infrastructure undoubtedly is a bottleneck for physical flows, its flexibility depends on the service reliability and resilience against failure. As transport infrastructure is often undersized (leading to congestion) and outdated (leading to deterioration and failures), infrastructure unavailability can cause multiple disruptions in the company's transport logistics (Stewart et al., 2011; Manfredi et al., 2018; Kotowska et al., 2018; An et al., 2015). Infrastructure bottlenecks ultimately cause losses in production capabilities at an affected location, again affecting the global SC. Therefore, we identify the necessity to analyze and improve the resilience capacity of SCs in relation to exogenous infrastructure conditions. In the first place, this requires a shared understanding, responsibility and collaboration between government and the private sector for transportation infrastructure, as it is the case already in the domain of other critical infrastructures (Trucco and Petrenj, 2017). To the best of our knowledge, little work exists on the link between SC performance and the availability of transportation infrastructure, which also takes the public decision perspective, i.e. infrastructure conditions for varying investment levels, into account.

In particular, our analysis identifies a promising opportunity to enhance domestic business locations by increasing infrastructure accessibility and availability. While standard literature on public policies of regional development focus on attracting new industries or firms, our approach takes a downside perspective: We determine the "threshold of pain" of infrastructure conditions which motivates firms to make the consequential decision to leave the area.

We focus on inland waterways as a special case of transportation infrastructure. This infrastructure represents a very interesting use case since it constitutes a critical bottleneck of the supply for specific industries due to their large-scale transport volumes and the rare redundancies of their wide-meshed transport network (European Court of Auditors, 2015).

Examining waterways as transport infrastructure, the (petro-)chemical industry with its foremost (liquid) bulk goods (van Hassel et al., 2018; Jetlund and Karimi, 2004) and a direct share of 30% on Inland Waterway transportation (IWT) in Germany (Figure D.1) becomes apparent as a key stakeholder.

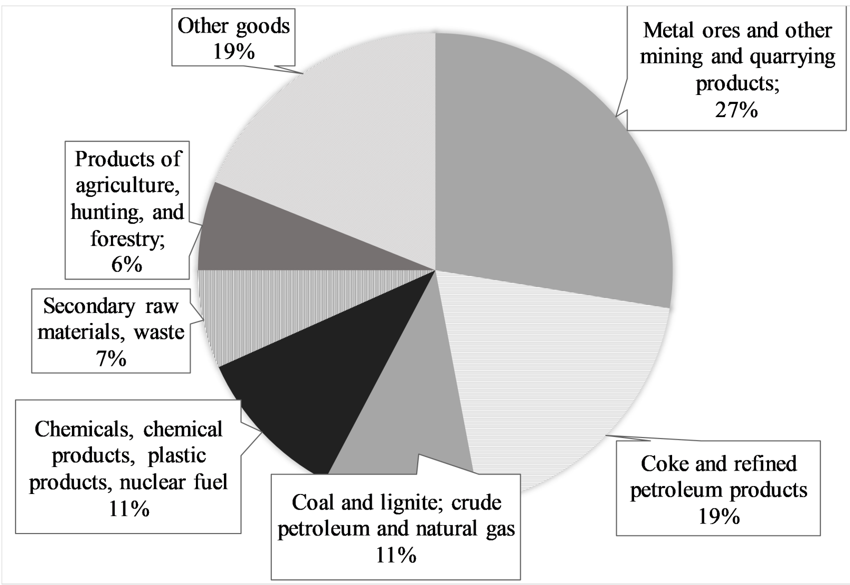

Figure D.1: Share of different types of goods in inland waterway transport in Germany (Federal Statistical Office of Germany, 2019)

Due to the condition of deteriorating infrastructure elements of German inland waterways and the chemical industry being heavily dependent on this infrastructure, we focus on the investment of public authorities' into infrastructure maintenance and the chemical industry as a key private stakeholder. From a methodological perspective, we formulate a Facility Location Planning (FLP) problem and link it to infrastructure maintenance. The developed model analyzes the influence of infrastructure availability on companies' decisions towards modal shift using a Vehicle Routing Problem approach and the possibility of relocating whole facilities using a FLP formulation. The output of the short-term operational logistics model is the input for the long-term, strategic decision. The last is based on a cost-driven utility function which determines the value of transport infrastructure availability for businesses.

The remainder of the paper is organized as follows: In Section D.2, we classify the research question according to the literature, specifically in the subject areas SC risk management and resilience, FLP and infrastructure availability as a location factor. Section D.3 presents the research approach, the formulation of the operational transport model (short term-focus) and the strategic relocation model (long term-focus). We apply the approach to the case study of the West German Canal Network in Section D.4. Section D.5 summarizes the findings, and in Section D.6 we close the elaboration with a discussion of the results and some concluding remarks.

D.2 Literature Review

D.2.1 Supply Chain Management and disruptions

SCs as backbone of economies interact with their environment in complex ways, triggered by mutual interrelations and feedbacks between themselves, nature, society, and the economy (Ivanov, 2020). They are characterized by interconnected firms being involved in transforming unprocessed raw materials into a final product and providing it to the consumer, while connections comprise flows of material, information and/or finance (Carter et al., 2015; Mentzer et al., 2001).

Multiple reasons might cause a SC to be permanently disrupted. The literature, for instance, lists pandemics (Chowdhury et al., 2021; Choi, 2021), terrorist attacks, labour strikes, human error and other causes affecting interdependent critical infrastructure, e.g. (Zhang et al., 2016). Disruptive events can cause a complete production or transportation stop and last for a long time, while typically, the probability of such catastrophic events to occur is rather low. Furthermore, they can either be independent of each other (e.g. a fire event in a certain plant) or correlated across the network (e.g. a tunnel breakdown affecting multiple plants in the region) (Lim et al., 2013). There are many conceptional studies, case reviews and optimization models regarding SCM (and even FLP as a specific approach; cf. Section D.2.3.1) that account for disruptions Snyder et al. (2016), Snyder and Daskin (2005) or Cui et al. (2010). However, empirical studies on SC-disruptions are still overly focussed on single events and andecdotical evidence. Therefore, systematic assessments of SC-disruptions and their effects are characterized by rather little evidence-based approaches due to the lack of data (Chowdhury et al., 2021). Choi (2021) also highlight the need for systematic analyses of logistics within vulnerable complex systems-of-systems (Eusgeld et al., 2011).

A global increase of 300% in catastrophic events from 1980 to 2017, as well as the total cost of disruption of $340 billion in 2017 alone, emphasize the threat to business and the need for robust SC design (Munich Re, 2018). Thus, SCs and related research revolve on transitions in trends from leanness and agility towards digitization, sustainability, and resilience (Ivanov, 2020).

To counteract rising risks, a functioning and effective SC Risk Management (SCRM) as part of SCM is indispensable (Bugert and Lasch, 2018). Studies in the literature frequently focus on operational and tactical factors of SC disruptions and SCRM, while strategic implications are often considered under the headings of vulnerability and resilience. These approaches predominantly focus on SC design (Wu et al., 2007; Yu et al., 2009; Hosseini et al., 2019) thereby neglecting the implications of short-term disruptions and external effects in the long run.

SC-resilience manifests when the network is capable to withstand and recover from disruptions to ensure performance (Hosseini et al., 2019). The recently introduced concept of SC viability aims to integrate the aspect of sustainability and resilience of SCs facing major disruptions endangering the continuity of SCs and associated business itself (Ivanov, 2020) in the long term. This includes aspects of business continuity management – questioning whether business activities of a company can be continued at a certain location. Whether this happens or not largely depends on the expected impact of disruptions on SCs, forcing companies to develop short-term contingency plans or use other tactical measures (Tang, 2006). Hence, strategies to manage SC disruption risks include mitigation and rerouting, depending on severity and frequency of disruptions (Tomlin, 2006).

The availability of transport infrastructure is of special interest in the context of SCRM due to the multiple dependencies within and among SCs (Heckmann et al., 2015), the above mentioned strategies to manage SC disruptions risks, and other SC stakeholders influencing the infrastructure's service performance. However, applying quantitative, context-sensitive models with emphasis on network characteristics is still a gap in SCRM (Heckmann et al., 2015; Qazi et al., 2017). Also, further research is required to assess geo-locations of disruptions, which is different for many SCs, i.e., based on their market distance (Bak, 2018). As further research efforts should explore the link between the availability of infrastructure at specific geo-locations and strategic SCRM decisions from a modelling side, this paper contributes to this gap as layed out by Li et al. (2016).

The analysis of link failures within SC networks comprises primarily network trip robustness and has only been used in transportation planning but not in FLP (Andronov and Jurkina, 2015; Taghizadeh and Hafezi, 2012). Moreover, specific works regarding links between inland waterway infrastructure and SCRM exist, e.g.: MacKenzie et al. (2012) analyze the consequences of inland waterway port closures and state that the modal shifts to rail cargo are the most likely company decision as a reaction due to a similar scalability of bulk good transport. Pant et al. (2015), moreover, investigate disruptions of inland waterway infrastructure in case of, among others, a two-week port disruption, and highlight the multi-regional industrial interdependencies. Beuthe et al. (2001) analyze intermodal freight transport based on GIS networks, considering demand elasticities. However, elaborations on costs of IWT in the intermodal context, as contributed by Wiegmans and Konings (2015) or Hintjens et al. (2020), are scarce.

D.2.2 Towards strategical implications

Melo et al. (2009) provide a short review about the planning levels of SCM (Figure D.2, left) and state a clear link between strategic SCM and the FLP in the planning context of SCM, SC network design and facility locations. Chatti and Zaabar (2012) furthermore observe that the condition of infrastructure clearly determines operating costs, while literature still has difficulties integrating the condition of infrastructure in the strategic decisions in SCM (Lambiase et al., 2013), not even considering exogenous factors (Gast et al., 2020). Next to that, today's SCs face multiple risks, arising from supply, process, demand, control and especially from the environment, since manifold external forces endanger business continuity (Christopher, 2016). Thereby, reliability, resilience and disruptions are closely linked in the literature but mostly pertain on the reliability of suppliers rather than the reliability of public transport infrastructure (Tomlin, 2006; Linnenluecke, 2017; Dolgui et al., 2018; Cavalcante et al., 2019).

To cope with disruptions, one can either reduce the likelihood or the impact of disruptions, whereas reducing the likelihood of exogenous events is regularly out of the scope of a single company (Tang, 2006). On the other hand, the probability of being affected can be reduced by withdrawing from the area of influence of a disruption. As we focus on the impact of a deteriorating transport infrastructure condition as a trigger for disruption, this problem area is determined by the state (and corresponding public authorities) as a distinct stakeholder besides the companies of the respective SC. In most countries, the public sector holds the primary responsibility for the investment in and thus the availability of transport infrastructure (Li et al., 2019). Figure D.2 summarizes the connections between the observed possible actions (decisions), impact mechanisms (arrows) and outcomes (availability in the short term, resilience in the long term) referring to transport infrastructure.

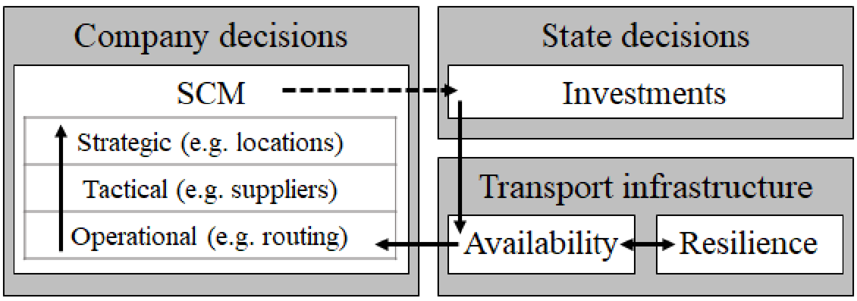

Figure D.2: Context of decisions

Figure D.2 shows that the transition from infrastructure availability to corporate decisions initially occurs at the operational level, e.g. with short-term measures such as modal shifts. However, if availability remains at a low level and the targeted short-term measures have to be taken repeatedly, the operational risk of infrastructure failure (i.e., lock closure) affects the strategic level. This implies the existence of a critical threshold and the question at what point a short-term measure like modal shift influences strategic decisions such as the planning of facility locations.

D.2.3 Facility Location Planning

D.2.3.1 Basics of FLP

As stated before, major strategic management decisions include FLP, which is used to resolve the classic type of location problem (Farahani et al., 2009). FLP models frequently apply mixed-integer programs where the co-domain of decision variables consists of discrete values (Daskin, 2011). While service-oriented FLP approaches aim to cover certain demand points (Current et al., 2002; Church and ReVelle, 1974), cost-oriented approaches consider optimizing covering distances as the p-center problem or aim to minimize the total travel distance as the p-median problem (Hakimi, 1964). Usually, solutions with a high service level are associated with high costs and vice versa. Thus, in many real-world FLPs, it is crucial to find a solution, which serves as an acceptable trade-off between both objectives. For instance, one model can be substituted into the remaining model as a bound, and then this bound can be varied systematically (Nozick, 2001).

Many FLP models further consider current and moreover exogenous conditions besides transportation costs, distances and service-level, such as spatial demand distributions, population and others (Farahani et al., 2009). Drezner (2014), e.g., provide a review of FLP considering the competitive environment of companies.

Further FLP models account for SC disruptions (Section D.2.1); reviews are e.g. provided by Snyder et al. (2016), Snyder and Daskin (2005) or Cui et al. (2010). In addition, the literature review by Snyder et al. (2016) identifies location planning as a possible measure to mitigate disruptions.

However, the focus of most FLP approaches is on the reliability of the facilities or internal SC elements rather than on continuous and exogenous factors like infrastructure. Snyder and Daskin (2005) e.g. extend the p-median problem to a multi-objective optimization problem with the objectives (1) original operating cost respectively and (2) the expected failure cost. Nevertheless, reliability is concerned with failure probabilities of facilities rather than transport infrastructure in this context (Zhang et al., 2016).

Thereby, infrastructure deterioration should have important significance in location issues, since not just the assignment of customers to plants is determined by the facilities' locations but also the amounts of freight to be transported are included in the considerations (Tapiero, 1971). Consequently, an available and accessible infrastructure is a prerequisite; otherwise production factors cannot access the production facility and produced goods cannot be delivered in time. Thus, overall, a deficient transport infrastructure leads to a major risk of SC disruptions. Due to the long-term nature of infrastructures (long construction and maintenance periods, continuous and steady demand), these disruptions usually imply long-term impairment of business activity.

D.2.3.2 FLP and the consideration of disruptions

An integral part of FLP in the field of disruption analysis (Choi, 2021; Tang, 2006; Tomlin, 2006) is the correct estimation of the SC reliability via the disruption probability. Albeit, according to Lim et al. (2013), managers tend to underestimate this probability and its impact because catastrophes happen rarely and reduced availability of transport infrastructure is hard to operationalize. Thus, they advise decision-makers rather to overestimate disruption probabilities, whereas budget restrictions mostly limit possibilities.

However, this paper is devoted to making infrastructure deterioration, uncertainties, and infrastructural costs explicit in the analysis. That is why catastrophes are not presented in greater detail at this point. While disruptions due to catastrophic events are characterized by rare occurrence and vary in their duration of impact (Cui et al., 2010), infrastructure availability is affecting SCs in the long-term. This is due to the combination of repair backlogs, maintenance durations and scarce resources in infrastructure construction (Wehrle et al., 2020).

D.2.3.3 FLP and the consideration of transport infrastructure

Few literature elaborates on FLP in combination with aspects of transport infrastructure. Examinations on the locations of companies depending on the transport infrastructure mostly focus on patterns in the spatial structure of companies and infrastructure (Button et al., 1995; Coetzee, Petrus J. van V. and Swanepoel, 2017; McCalla et al., 2001; Shukla and Waddell, 1991). Canbolat et al. (2007), e.g., use a framework of decision tree and multi-attribute utility theory (MAUT) to evaluate different countries as potential sites. They use aggregated factors such as geographic and demographic location, which is influenced by the quality of a country's infrastructure, which in turn is represented by an overall performance indicator generated by a limited number of interviews (Canbolat et al., 2007).

Hajibabai et al. (2014) use an integrated FLP model to consider the joint optimization of freight facility location and pavement infrastructure rehabilitation since heavy trucks cause a periodic threat to pavement conditions on highways. Rehabilitation activities are furthermore seen as discrete jumps in pavement condition, which directly influence the user cost. Nevertheless, Hajibabai et al. (2014) neglect the possibility of modal shifts and focus on the special case of road infrastructure, which differs by the transmission of infrastructure condition towards direct impacts on user cost.

Overall, none of the observed FLP models meets the authors' requirements since the beforementioned FLP approaches are predominately used when companies perform basic evaluations on one or more location(s) for one or more new site(s). Regarding degrading infrastructure and existing highly infrastructure-dependent facilities, two main aspects are essential to consider: Firstly, attempts of companies to relocate their existing facilities (or parts of it) towards locations where a better infrastructure performance can be reached and secondly, a valid method to connect long-term infrastructure availability, location decisions and short-term logistics decisions. That is because maintaining a facility can be more costly than relocating it to another site (Farahani et al., 2009) and because the accessibility of reliable transport infrastructures plays a vital role in companies' location decisions (Mejia-Dorantes et al., 2012), as infrastructure is the most important factor in logistics performance (Rezaei et al., 2018). Due to the critical role of location planning in SCM considerations, this paper examines research among the relocation of firms in the following subsection before we focus on infrastructure maintenance.

D.2.4 Towards relocation implications

D.2.4.1 Location-Relocation Problem

Relocation considerations are investigated mostly by starting with a baseline allocation of facilities and allowing systematic facility relocation. However, the first general considerations of relocation focus on dynamic location plans which are based on periodically reviews of foremost static location models, thereby maximizing "cumulative profits from location and relocation" (Ballou, 1968). Heuristics, limiting possible configurations, as well as optimal multi-period solutions of limited numbers of alternatives, are derived under the heading of dynamic FLP at an early stage (Sweeney and Tatham, 1976; Wesolowsky, 1973; Bastian and Volkmer, 1992; Hormozi and Khumawala, 1996). Boloori Arabani and Farahani (2012) and Seyedhosseini et al. (2016) provide more recent reviews on dynamic location problems, addressing the combined facility location-relocation problem, as relocation is a common strategical decision of firms (Boloori Arabani and Farahani, 2012).

As for the basic FLP, long periods between the decision and implementation of (re-)locations (Chand, 1988) result in the need for the most accurate predictions possible. Moreover, relocation must also take into account the process of closing former locations (Ballou, 1968). In general, the following points are crucial to consider when it comes to relocation decisions (Boloori Arabani and Farahani, 2012):

(1) time of relocation
(2) number of relocations
(3) cost of relocation (land acquisition, zoning permits, building construction, moving equipment/personnel, etc.)
(4) accessibility and quick delivery to customers
(5) reachability to suppliers
(6) easy access to transportation networks
(7) tax incentives
(8) quality of labour, and
(9) labour-management relations.

The literature distinguishes between discrete and continuous relocation and between implicit dynamic and explicit dynamic facility location models (Farahani et al., 2009). Nevertheless, the focus is on minimizing costs regarding the location of facilities among potential locations and allocating them towards respective demands (Wesolowsky and Truscott, 1975).Farahani et al. (2009), e.g., investigate a time-dependent single FLP with multiple relocation opportunities by minimizing total location and relocation costs and investigate the optimal time to relocate. Albeit, since they focus on distance measures towards demand points, they neglect congestion phenomena, infrastructure availability or accessibility.

Literature on relocation is not limited to production sites or warehouses, but also includes headquarters which are mostly disconnected from production sites, drawing implications on the welfare of workers (Fujita and Thisse, 2006) or also on infrastructural needs as improving airport facilities or the implication of lowering taxes (Strauss-Kahn and Vives, 2009). These works demonstrate once more the link between corporate decisions, relocations and claims and implications on the decisions of public authorities.

Nevertheless, classical location-relocation problems appear not to solve the requirements to derive implications on decisions of public authorities by investigating the influence of infrastructure availability on both operational and strategical companies decisions. Other attempts on investigating relocation include the analysis of relocation patterns, as Jiang et al. (2018) do based on empirical data and percolation theory. In this context, the authors highlight the scarce literature on empirical studies about industrial relocation before stressing the importance of considering all available modes of transport. They recognize interdependencies between transport accessibility and the probability of cities as relocation destinations but rather focus on the electronics and information industries, implying industry-specific constraints.

de Bok (2009) suggest another method to evaluate the probability of facilities to relocate. They examine the influence of accessibility and agglomeration on the behaviour of firms in terms of company relocation, growth, dissolution or company foundation, tested with a microscopic model of company dynamics based on the following formula:

$$P_{Relocate}(t) = \frac{1}{1 + e^{-u(t)}} \qquad \text{(Exp. D.1)}$$

where $\mathrm{u(t)}$ is a utility function, depending on the aforementioned parameters. Both the utility and probability of relocating are time-dependent (de Bok, 2009).

D.2.5 Infrastructure maintenance and business locations

D.2.5.1 Infrastructure as location factor

The most relevant determinants of international competitiveness are geographical factors and transport infrastructure, as the distance between a region and its main trading factors determines logistics success (Bensassi et al., 2015). Infrastructure is seen as the most essential location factor of business locations (Rezaei et al., 2018) and a key driver of economic growth, especially in the long-run (Hong et al., 2011; Pradhan, 2019; Ahmed et al., 2021; Cigu et al., 2019). When considered as an object of analysis, infrastructure as public capital "can be analyzed as private good provided by the government"(Zepeda Ortega et al., 2019), according to Barro and Sala-i Martin (2001). Meanwhile, transport infrastructure networks and SC networks must be considered together to enable and prevent efficient and sustainable economies (Yamada and Febri, 2015; van de Vooren, 2004), whereas examinations connecting water-borne infrastructure maintenance and economic performance is scarce (Feng et al., 2020).

D.2.5.2 Inland Waterways

All kinds of transport infrastructure are a driver of sustainable economic growth (Gherghina et al., 2018). Especially Inland Waterways can highly contribute to sustainable development since they provide advantages like high energy/fuel efficiency, relatively low transport costs for bulk goods, the possibility of transporting large and heavy goods, savings in storage time and costs and reduced number of accidents (Borodulina and Pantina, 2021; Gherghina et al., 2018). As for any type of infrastructure, water transport infrastructure entails investment thresholds above which a significant positive contribution to economic growth is established through the provision of infrastructure service and performance (Hong et al., 2011). Therefore, inland waterways should be maintained efficiently to enhance the sustainable development of regional business locations which are dependent on IWT (Oztanriseven and Nachtmann, 2020).

Beyond the aforementioned elaborations, waterways are now an increasing subject of research (Sys et al., 2020). Oztanriseven and Nachtmann (2020) propose an extensive model (MatTranS) to support informed inland waterway infrastructure decisions by analyzing infrastructure components and their associated economic impacts. The methodology is based on various models with different levels of detail, including system dynamics, which is complex to reconstruct.

D.2.5.3 Infrastructure maintenance

Maintenance measures are seldomly prioritized effectively according to their impact on commercial traffic but instead on regulatory requirements. Moreover, the prioritization methodology does not consider the impact of infrastructure failures due to delayed maintenance on port operations and affected companies. This negligence potentially leads to systematic underinvestment by public infrastructure providers. As a consequence, firms avoid using this infrastructure. Therefore, strategical implications on decision-makers should focus on measures which strengthen infrastructure condition (Pradhan, 2019).

Effects of neglected maintenance can be modelled as an impact on transportation time, depending on traffic intensity, capacity and empirical parameters as done by Chatti and Zaabar (2012), whereas they focus on roads and the specific case of pavement deterioration while modal shifts are not considered. Ke and Verma (2021) examine intermodal rail-truck networks, referring to disruption risks based on capacity reductions, but also neglect maintenance measure potentials. Moreover, incidents, bottlenecks, and special events must be taken into consideration to determine the traffic situation, among others (Kwon et al., 2011).

Chatti and Zaabar (2012) also consider the public cost for pavement repair as a function of road length, deterioration rate and traffic volume and material properties, among others.

Since critical transportation infrastructure is predominantly made of concrete, corrosion of concrete reinforcement is a major threat to the reliability of all transportation assets. Furthermore, increasing CO2-concentration in the atmosphere increases the threat and damage incidents caused by up to over 400% by the year 2100, as Stewart et al. (2011) show in their time-dependent reliability analysis considering corrosion initiation and damage to infrastructure.

Bensassi et al. (2015) provide an overview of logistics indices and determinants in literature while we focus on the Logistics Performance Index (LPI) as an established metric considering available performance data based on empirical research related to ports, roads, rail and air transport (The World Bank, 2018). Thereby, six factors are regarded as being equally important, whereas the weighted LPI (Rezaei et al., 2018) states that infrastructure is the most important component (weight of 0.24) and tracking and tracing is the least important indicator (weight of 0.10).

D.2.5.4 Infrastructure availability

Transport infrastructure must be both accessible and available to ensure a reliable use. Location planning usually focuses on accessibility if considering transport infrastructure (de Bok, 2009), which is determined by local conditions and the geographical location of the infrastructure. However, the literature is vague about the distinction between accessibility and availability. For instance, the density of a road network is sometimes used as a measure of the availability of road infrastructure (Zepeda Ortega et al., 2019). However, road density is rather attributable to accessibility. Furthermore, network performance can be linked to network-disruption indices as change in travel times resulting from shifted transports due to link failures (Sullivan et al., 2010). Gu et al. (2020) provide a review on transportation network disruptions with reliability concerns, delimiting reliability, vulnerability, and resilience, emphasizing the need for research considering multi-modal networks. Mohammadi et al. (2019), moreover, investigate multi-modal hub locations under disruptions, reflecting the vulnerability of transport networks.

Availability, moreover, refers to the condition or capacity of infrastructure and, as such, is threatened by disruptions like malevolent attacks, human-technical failure or natural disasters. Gast and Wehrle (2019) present an availability assessment model for Inland Waterways based on reliability theory. In their approach, availability (A) is assigned to an infrastructure element using the statistical values of Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR) according to Exp. D.2:

$$A = \frac{MTBF}{MTTR + MTBF} \qquad \text{(Exp. D.2)}$$

Furthermore, the availability of a whole system or single transport way can be derived by calculating the availabilities of the infrastructural elements in their network configuration (Gast and Wehrle, 2019).

D.3 Research Methodology

D.3.1 Concept

Figure D.3 shows the foundations of this paper's research concept, which is based on the assumption that the reduction of the availability of transport infrastructure influences business decisions. Whereas short-term reductions lead to modal shift decisions towards alternative modes, long-term reductions in availability may even lead to shifting entire facilities as relocation decisions. Moreover, operational and strategic decisions are linked by the capacity of competing transport modes, as modal shifts are prevented by a lack of capacity, driving the need for relocation.

Deteriorating condition due to a lack of maintenance resources directly impact the availability of the infrastructure network. Therefore, the research question is how the availability of transport infrastructure influences company relocation considerations. Moreover, we formulate the following sub-questions:

(1) How can cost increases resulting from unavailable infrastructure elements be assessed?
(2) How can the current infrastructure availability be assessed?
(3) What are the costs of infrastructure unavailability?
(4) Which decrease in availability will trigger firm relocations?

To this end, a transport model (Section D.3.2) is considered to assess the cost increases incurred by a company as a result of the failure of infrastructure elements. Based on this, a relocation model (Section D.3.3) examines the impact of the corresponding cost increase due to the reduction in availability on the preservation or relocation of existing industrial sites. Finally, a company's utility function evaluates the outcomes of these decisions. The model components are explained in detail in the following subsections.

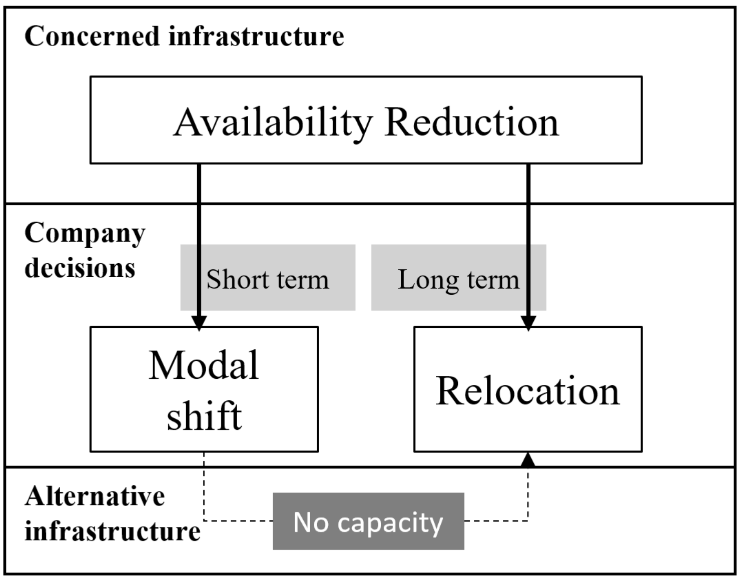

Figure D.3: Concept of research

D.3.2 Transport model

To answer our first subquestion *(How can cost increases resulting from unavailable infrastructure elements be assessed?)*, we set up a transport model fulfilling the demand of waterway transport to analyse the impacts of infrastructure failure on transport cost. (Tavasszy et al., 2012) outline two relevant research avenues from their literature review on freight transport demand modelling. The first avenue is a choice model when little information about the SCs and underlying transport infrastructure is available. The second avenue is linking supply and demand via multiple networks. Both are taken into account by modelling a bi-objective multi-vehicle routing problem that consists of selecting transportation modes for respective transport quantities and allocating these shipments to available ports in a waterways network, according to Binsfeld (2020). The vehicle routing is based on the Traveling Purchaser Problem (TPP) that is defined as follows: a vehicle visits a number of suppliers who sell a set of products at different prices to be in the right quantity of each product and use it to satisfy the deterministic demand for each product at a minimum cost level (Cheaitou et al., 2020).

How to consider bimodal transport routing options in supply chains between different SC agents like manufacturer, carrier, and customers has been, for example, shown by (Yamada and Febri, 2015b) who analyze a fictive network and determine the equilibrium where all supply and demand are matched. As only several demand levels at ports are known in the West German canal network but no supply origins, a TPP formulation links supply at the system's border with the demand. Thus, the model determines the minimal transport costs possible to satisfy total demand under the simplifying assumption of full collaboration of carriers to satisfy the ports' demand, which results in tramp shipping and less direct transport. The same goes for the scenario-based analysis of infrastructure failure. From the assumptions follows that the model's results represent a lower bound in the sense that the actual cost increase would "not be lower" than the determined Δc_S.

In our approach, accessibility points to the inland waterway infrastructure are determined by the nearest accessible port (or, e.g., highway node). From a company's perspective, accessibility scores represent a cost weight of availability. If the nearest port is unavailable and thus not accessible, the distance delta to access the next available port represents the cost of accessibility. The model provides insights on multimodal transportation and the impact on the choice of transportation mode by calculation of the total costs and emissions aiming at an efficient match of supply and demand. While using a cost function proposed by the German federal institution and an emission function based on German DIN EN 16258 (DIN, 2013), the results are reliable and ensure external validity. Different scenarios are implemented based on real-world data which are aligned with the cases discussed in the next section (Binsfeld, 2020).

The objective function Exp. (D.9) minimises the total transportation costs, while the supply of goods by waterway transport and trucks is compared. Thereby, we derive the cost impact of ports not being accessible by waterway due to infrastructure failure and extra cost of trucking to these ports to meet their demand.

The formulas are as follows, according to Binsfeld (2020).:

Distance related costs (DC):

$$DC = \sum_i \sum_j \sum_k \sum_m (\alpha^{km} + \beta^{km} + n^{km}) \cdot (\frac{d_{ij}^{km}}{s^{k,m}} + q_{ij} \cdot \tau) \cdot x_{ij}^{km} \quad \text{(Exp. D.3)}$$

Docking related costs (DoC):

$$DoC = \sum_i \sum_k \sum_m h \cdot (\alpha^{km} + \beta^{km} + n^{km}) \cdot y_i^{km} \quad \text{(Exp. D.4)}$$

Freight quantity related costs (FQC):

$$FQC = \sum_i \sum_j \sum_k \sum_m \frac{\alpha^{km} + \beta^{km} + n^{km}}{\eta} \cdot f_{ij}^{km} \quad \text{(Exp. D.5)}$$

Fuel related costs (FuC):

$$FuC = \sum_i \sum_j \sum_k \sum_m \frac{d_{i,j}^{km}}{s^{km}} \cdot \mu^{km} \cdot x_{ij}^{km} \quad \text{(Exp. D.6)}$$

Unloading related costs at the ports (PC):

$$PC = \sum_i \sum_k \sum_m (\phi + \epsilon^{k,m}) \cdot Q_i^{k,m} \quad \text{(Exp. D.7)}$$

Loading related costs from one transportation mode to the other (LC):

$$LC = \sum_i \sum_k \sum_m \gamma^{k,m} \cdot UQ_i^{km} \quad \text{(Exp. D.8)}$$

The above costs are aggregated to formulate the Total costs for IWT (TC) [EUR]:

$$TC = DC + DoC + FQC + FuC + PC + LC \quad \text{(Exp. D.9)}$$

Thereby, m represents transportation and shipping modes in parallel, since the cost parameters for one mode can be zero if there is no activity (i.e., no demurrage costs for trucks, but only for ships).

Table D.1 provides an overview of all the variables used to eventually determine total costs and transport costs between supply and demand ports in the system.

The process of the transportation model can be summarized as follows:

(1) Identification of locations of ports, the navigable canals and infrastructure buildings b are identified.
(2) Selection of routes for shipping of the capacitated vehicles under which the transport cost in the system is minimized while eventually all demand is met.
(3) Removal of possible network connections to simulate infrastructure failure, and the optimization model is rerun. This way, the following is achieved:

Notation	Description	Unit
$\alpha^{k,m}$	Vehicle related costs such as depreciation, repairing, capital costs, insurance	EUR/h
$C^{k,m}$	Capacity of ship/truck k	t
$\beta^{k,m}$	Personnel costs per worker	EUR/h
$n^{k,m}$	Number of personnel depending on vehicle	
$d_{i,j}^{k,m}$	Distance between ports i and j using vehicle k of the ships	km
$q_{i,j}$	Number of locks between ports i and j	
$Q_i^{k,m}$	Quantity for port i loaded at vehicle k with mode m	
$U_i^{k,m}$	Unloaded quantity at port i using vehicle k with mode m	
h	Docking time at port	h
τ	Lock times at locks	h
η	Handling performance depending on industry	t/h
$\mu^{k,m}$	Fuel costs depending on ship performance	EUR/km
ϕ	Port costs of ship while unloading	EUR/t
$\epsilon^{k,m}$	Unloading costs at port	EUR/t
$\gamma^{k,m}$	Loading costs at other transportation mode	EUR/t
$s^{k,m}$	Speed of ship/truck k	hm/h

Table D.1: Notations and description of transport model

(a) Cost model: Failure of an infrastructure element b on the route i, j increases transport costs by Δc_b

(b) the aggregation of routes with the - potentially failing - infrastructure elements on them leads to the scenario (s) which results in a cost increase Δc_s.

The scenario-based cost increase is deterministic and describes the mechanism of how transports reroute or shift modes to fulfil demand which results in relative cost increases $\Delta c_{i,j}$ to supply port i from port j in case of infrastructure failure on the way. This cost increase now directly affects a company located at port j. The following section shows how historical data allows us to derive a stochastic availability that is considered in the formulation of risk scenarios Θ_i.

D.3.3 Relocation model

The relocation model aims to answer the previously stated research question and sub-questions (2) - (4) to assess the current availability and the corresponding costs of infrastructure unavailability. Moreover, the relocation model derives the firms' "threshold of pain", the critical threshold for a decrease in availability which causes relocation.

Based on the previous elaborations, our fundamental assumption states the existence of critical thresholds for the availability of infrastructure, below which it is only worthwhile for companies to relocate one or more facilities. The determination of these availability thresholds depends on transport costs (operational) and relocation costs (strategic). The costs can be represented by a utility function, according to de Bok (2009), reflecting the benefits that companies derive from access to a functioning infrastructure and corresponding reductions in utility that result from a reduction in availability. Hence, we perform the following steps sequentially:

(1) Risk calculation
   (a) incorporation of availability $\Delta c_s(A_s) = \Delta c_s \cdot (1 - A_s)$, according to calculation and empirical data from Gast and Wehrle (2019)
   (b) formulation of risk scenarios Θ_i (formation of scenarios i, which represent different risk potentials)
   (c) calculation of escalated costs $\Delta c_{s,\Theta_i}(A_s) = \Delta c_s(A_s) \cdot \Theta_i$
(2) Calculation of the cost dependent probability to relocate (derivation of the cost-dependent probability for relocation)
   (a) anticipation of costs for relocation $c_R(\Delta c_s)$ as a function of transportation costs
   (b) calculation of Probability

$$P_R(A_s) = \min\Big\{ \max\big\{0; \Delta c_{s,\Theta_i}(A_s) - c_R\big\}; 1\Big\} \qquad \text{(Exp. D.10)}$$

(3) Set k availability thresholds $A_{t1}, ..., A_{tk}$ (determination of k potential critical threshold levels of availability $A_{t1}, A_{t2}, ...A_{tk}$, based on empirical data)
(4) Derivation of the utility-based probability to relocate, i.e. formulation of the probability to relocate in dependence of utility, according to de Bok (2009):

$$P_R(u) = \frac{1}{1 + e^{-u}} \qquad \text{(Exp. D.11)}$$

with

$$u = \beta \cdot A_s + (1 - \beta) \cdot LPI + \alpha \qquad \text{(Exp. D.12)}$$

with

$$\alpha, \beta \in [0; 1] \qquad \text{(Exp. D.13)}$$

Referring to the first step and first sub-question, we apply the concept of infrastructure availability as depicted in Section D.2.5.4. Thus, availability can be calculated via empirical data on failure times. The escalation parameter used to form the risk potentials represents not only a time parameter but also a resilience factor and thus includes the company's vulnerability in addition to the duration of the disruption. The factor represents revenue reductions as well as increases in production costs as an influence on the profit margin. The escalation parameter shows how severely short-term increases in operating costs affect business activity if, for example, the disruption duration and the company's vulnerability are at their maximum in the highest escalation level $\Theta_{i_{max}}$.

The result primarily provides an assessment of the current situation, as the current availability is set into relation to the cost and utility function(s). Thereby, we provide an answer to our sub-question (2) and can derive recommendations for actions about infrastructure maintenance in the form (examples): "is currently already at a critical point, prioritize maintenance here", "Availability shows an absolute increase once preventing manageable failures", ... "currently not problematic, but if the availability falls below a critical value, actions are required". We get the costs of unavailable infrastructure (sub-question 3) by combining relocation and transport model, as the first step of our relocation model provides the calculation of scenario-specific escalated costs. The outcome of our model serves to answer the last sub-question (*Which decreases in availability will cause relocations?*), as the utility-based probability assessment incorporates both preferences of companies and transportation costs from the transport model.

D.4 Case

D.4.1 West German Canal Network

The developed methodology is applied to the West German Canal Network (WGCN), which is illustrated in Figure D.4, representing the first step of data extraction as part of the transport model. The existing locks are shown iconized in blue, and most of them comprise two chambers (Gast and Wehrle, 2019). Moreover, the harbours are depicted with an anchor symbol, representing all varieties of harbours from small to big which are covered by (Federal Statistical Office of Germany, 2019).

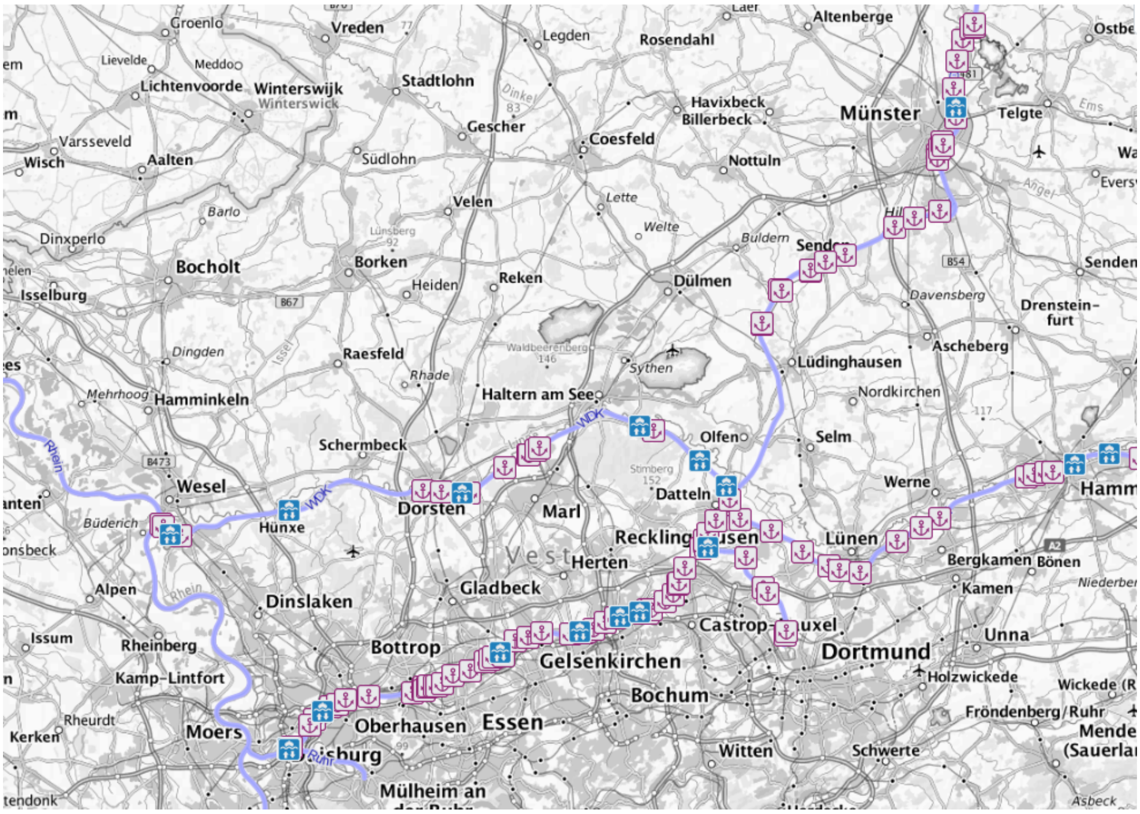

Figure D.4: West German Canal Network with depicted locks and harbours

The choice of the model region is based on the fact that it exhibits a waterway network that is comparatively close-meshed and thus implies inevitable redundancies in the modal choice of transports which, however, cannot always be used due to capacities and unsuitable ship sizes. In addition, the alternative transport modes of road and rail are densely linked in the region under consideration, as are numerous loading options via ports and transshipment stations. Another essential factor is the high industrial density of companies that operate on the waterway (Gast et al., 2020) which are the focus of our analysis. In North-Rhine Westphalia, where the WGCN is located, waterway transport represents up to 30% of the modal split (Federal Statistical Office of Germany, 2019). Another advantage of the model region lies in notifications-to-skippers (Gast et al., 2020) and the corresponding open data policy that facilitates data acquisition.

D.4.2 Transport Model

The procedure described in Section D.3.2 is conducted as follows.

Step 1 (Identify locations): Locations of harbours and infrastructure buildings are derived from available geodata as depicted in Figure D.4. Data on company locations is obtained from publicly available data. Routes of shipping are assessed based on the transport model that aims to satisfy port demand based on databases (Federal Statistical Office of Germany, 2019) with lowest cost (Binsfeld, 2020).

Step 2: Expected costs of route-failure are calculated based on scenarios of failed locks which are transferable to failures between two corresponding harbours. Case (3), for instance, involves alternative failures of the direct successive locks Wanne-Eickel and Herne Ost, which in turn can be transferred to interruptions between the ports of Wanne-Eickel and (a) Dortmund, (b) Lünen, (c) Marl Hüls and (d) Münster, which lie along the way. The result is the scenario-specific percentage increase of transport costs Δc_s as illustrated by Table D.2.

Scenario s	Lock designation b	Scenario cost increase	Δc_s	Availability$_b$	A_s	$1 - A_s$	$\Delta c_s(A_s)$	$\Delta c_{s,\Theta_1}(A_s)$	$\Delta c_{s,\Theta_2}(A_s)$	$\Delta c_{s,\Theta_3}(A_s)$
1	Meiderich	1.1093331	10.93%	77.20%	77.200%	22.800%	2.493%	2.493%	24.927%	249.275%
2	Gelsenkirchen	1.0869440	8.69%	88.63%	88.630%	11.370%	0.989%	0.989%	9.885%	98.854%
3	Herne Ost	1.0047022	0.47%	80.99%	77.637%	22.363%	0.105%	0.105%	1.052%	10.516%
	Wanne Eickel	1.0047022		95.87%						
4	Henrichenburg	1.0522281	5.22%	95.94%	95.943%	4.057%	0.212%	0.212%	2.119%	21.191%
5	Ahsen	1.0405092	4.05%	74.04%	45.284%	54.716%	2.217%	2.217%	22.165%	221.652%
	Datteln	1.0405092		71.04%						
	Flaesheim	1.0405092		86.09%						
6	Dorsten	1.1642450	16.42%	76.54%	45.883%	54.117%	8.888%	8.888%	88.884%	888.840%
	Friedrichsfeld	1.1642450		71.95%						
	Hünxe	1.1642450		83.32%						
7	Hamm	1.0551674	5.52%	97.64%	97.643%	2.357%	0.130%	0.130%	1.300%	13.002%
8	Münster	1.0377451	3.77%	98.09%	98.085%	1.915%	0.072%	0.072%	0.723%	7.227%

Table D.2: Calculation of the case-based cost-increases

The authors compare the supply of goods of the chemical industry in the WGCN by IWT and trucks. A sensitivity analysis of infrastructure failure scenarios obtains the cost impact of ports not being accessible by waterway due to infrastructure failure and extra cost of trucking to these ports to meet their demand. The results show a cost increase of up to 16.42% for the whole system for case 6 (Table D.2).

D.4.3 Relocation Model

D.4.3.1 Risk calculation

Table D.2 furthermore shows the results of the risk calculation (Step 1) of the relocation model (cf. Section D.3.3). First, a comparison of increasing cost due to the unavailability, which is derived from historical data (Gast and Wehrle, 2019), is performed before formulating $i = 3$ risk scenarios that lead to the corresponding escalated costs $\Delta c_{s,\Theta_i}$. Figure D.5 illustrates the results of the transport model and the corresponding availabilities derived from the above mentioned historical data.

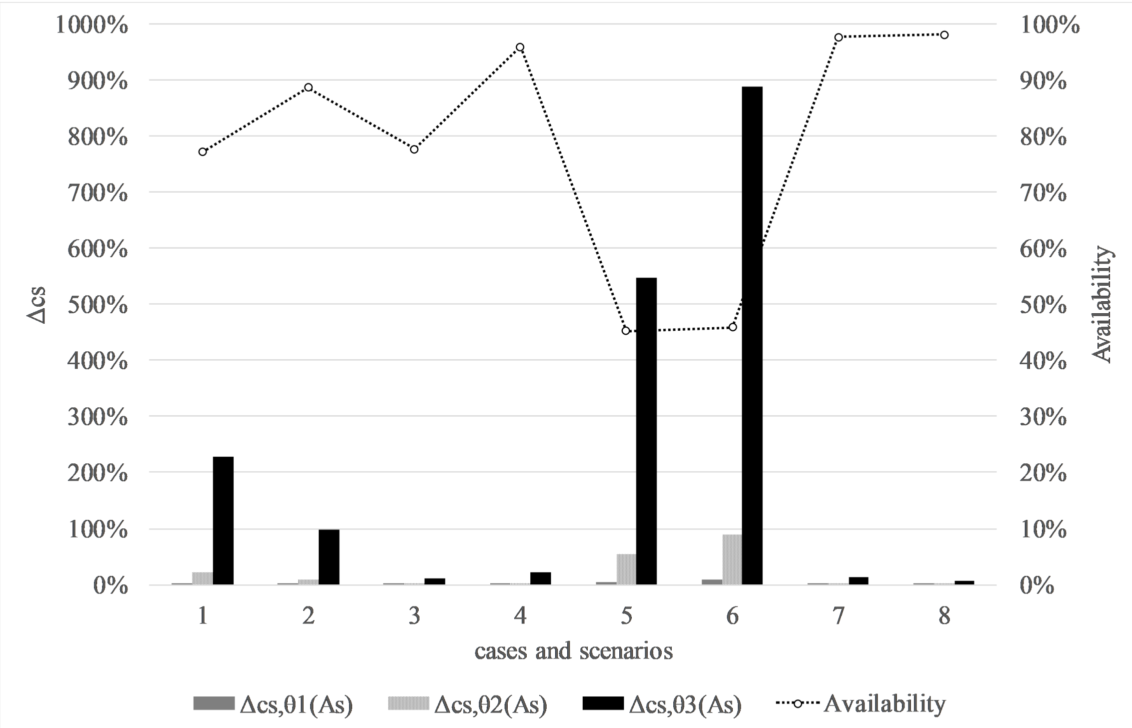

Figure D.5: Scenario-based cost increase and availability at the West German Canal Network

The escalating parameters Θ_i are set to $\Theta_i = 1, 10, 100$ and include the assumptions depicted in Table D.3, based, among others, on Gast et al. (2020), analyzing 14 days of disrupted waterways as a critical threshold to business activities. The proposed factors take into account the fact that longer disruptions and more vulnerable company locations lead to extensively increased costs and loss of revenue, which, based on the reflections of Figure D.3, lead to long-term considerations and even to business abandonment.

	factor	duration of disruption [days]	Vulnerability
Θ_1	1	$d < 13$	low
Θ_2	10	$14 \leq d \leq 28$	medium
Θ_3	100	$29 > d$	high

Table D.3: Definition of escalation parameters

D.4.3.2 Cost dependent probability to relocate

Based on these calculations, we proceed with Step 2 and derive the cost-dependent probability for relocation. Therefore, the costs for relocation Δc_R are assessed on three levels, each related to the operational transport costs, based on sensitivity analyses: $\Delta c_{R_0} = 100\%$, $\Delta c_{R_1} = 250\%$ and $\Delta c_{R_2} = 500\%$. Figure D.6 illustrates for each scenario the cost increase over time from Table D.2), showing in horizontal red lines Δc_{R_0}, Δc_{R_1} and Δc_{R_2}.

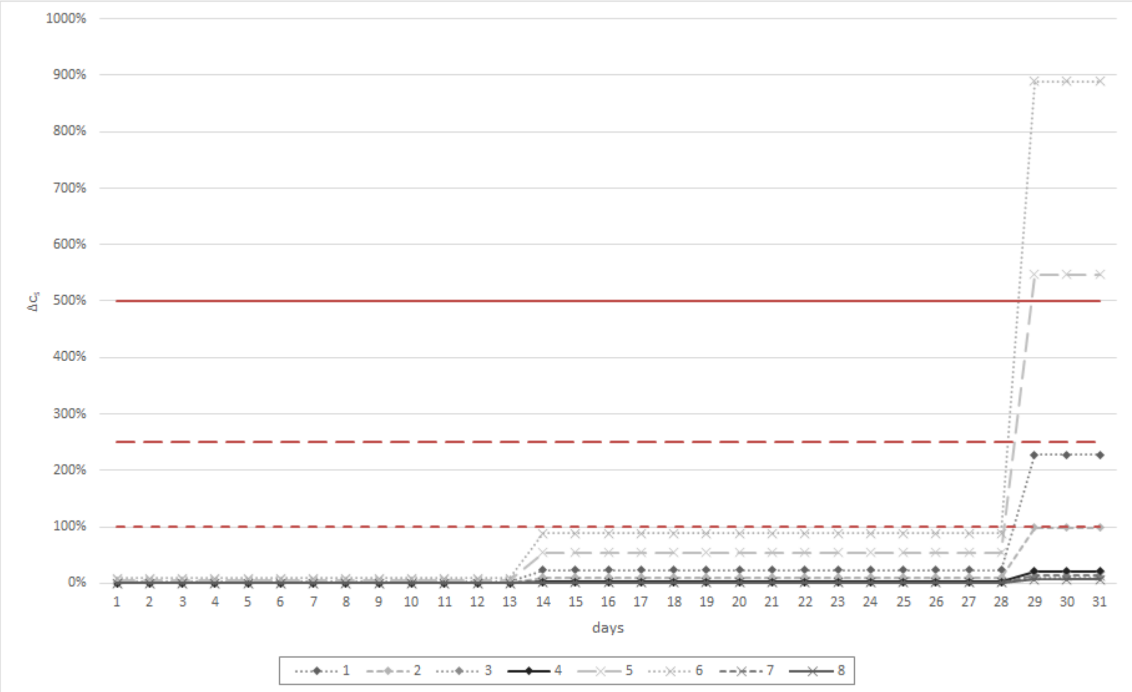

Figure D.6: Scenario-based cost increase over time at the West German Canal Network

The interrelation between cost increase and infrastructure availability (Figure D.7) shows that a linear approximation within the respective risk potentials is roughly possible.

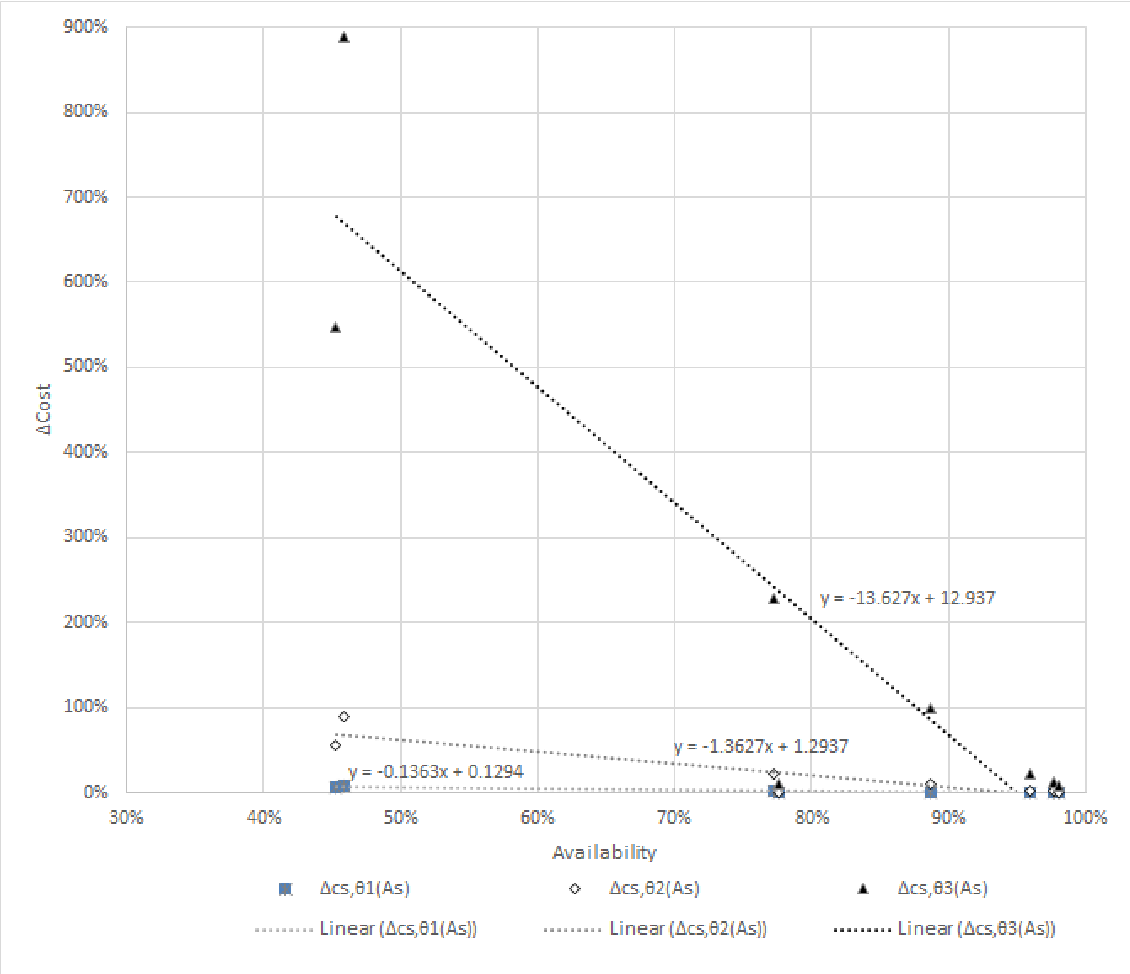

Figure D.7: Interrelation between cost increase and availability

To calculate the probability to relocate, the authors use Figure D.8, revealing turning points in the formula of the calculated probability at

$$A_{\Theta,\Delta c_s,c_R}(u) = \max\left\{\frac{100\cdot\Delta c_s\cdot\Theta - 100\cdot c_R - 50}{\Delta c_s\cdot\Theta};0\right\} \qquad \text{(Exp. D.14)}$$

D.4.3.3 Availability thresholds

Based on this, we set critical thresholds of availability in the range of the identified turning points (Table D.4). Availability levels are set in increments of 10 percentage points, starting at 50% and approaching perfect availability more closely, thus examining the following thresholds:

$$A_t = \{50;60;70;80;85;90;95;99;100\} \qquad \text{(Exp. D.15)}$$

Scenario	Cost	Θ_1			Θ_2			Θ_3		
		Δc_{R_0}	Δc_{R_1}	Δc_{R_3}	Δc_{R_0}	Δc_{R_1}	Δc_{R_3}	Δc_{R_0}	Δc_{R_1}	Δc_{R_3}
1	1.109	0.000	0.000	0.000	0.000	0.000	0.000	86.280	72.561	49.695
2	1.087	0.000	0.000	0.000	0.000	0.000	0.000	82.748	65.495	36.741
3	1.005	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4	1.052	0.000	0.000	0.000	0.000	0.000	0.000	71.280	42.560	0.000
5	1.041	0.000	0.000	0.000	0.000	0.000	0.000	62.971	25.943	0.000
6	1.164	0.000	0.000	0.000	8.673	0.000	0.000	90.867	81.735	66.513
7	1.055	0.000	0.000	0.000	0.000	0.000	0.000	72.810	45.620	0.303
8	1.038	0.000	0.000	0.000	0.000	0.000	0.000	60.260	20.519	0.000

Table D.4: Turning points of infrastructure availability, determining probability to relocate in accordance to Exp. D.14

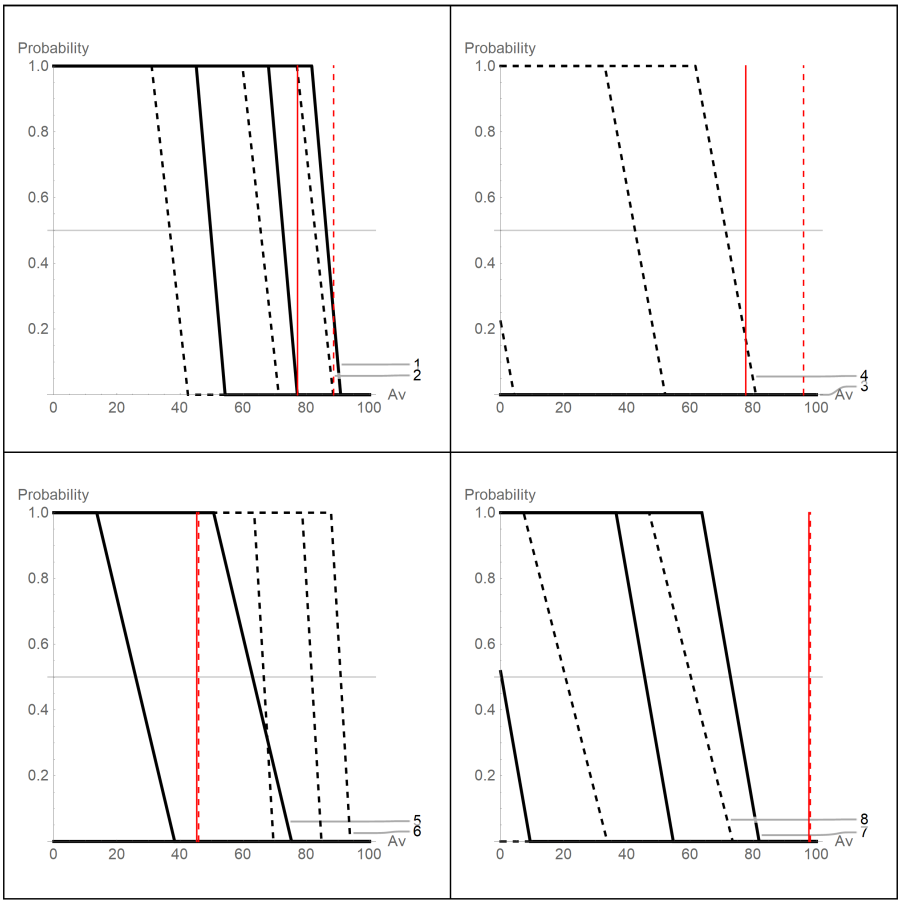

Figure D.8: Probability to relocate in dependency of infrastructure availability (Av)[2]

[2] Each graph comprises two scenarios (1 line, 2 dashed, etc.) and the three considered levels of relocation costs Δc_R, whereas the most right (black) lines refer to the assumption of $\Delta c_R = 100\% \Delta c_s$. The red lines illustrate the respective current availabilities A_s.

These levels allow for further analyses on distributions of the current availability as percentage of cases below and above the thresholds. Thus, the allocation of infrastructure investments may be prioritized by focusing on those routes (cases), which significantly fall below the thresholds.

D.4.3.4 Utility-based probability to relocate

Based on these steps, we derive the utility-based probability to relocate, assuming a utility function depending on availability and LPI, whereby the latter in our case is quantified by the value 4.2, having a maximum value of 5, which is normalized in the following. Exp. D.10 and Exp. D.11 yield a turning point of the utility-based function at

$$A_t = \frac{-\alpha + (1-\beta)\cdot\frac{LPI}{5}}{\beta} \tag{Exp. D.16}$$

Equating this with the identified threshold levels to identify the function parameters allows the applicant to parametrise the utility function which reflects a company's benefits from transportation infrastructures. Figure D.9 shows the parametrization.

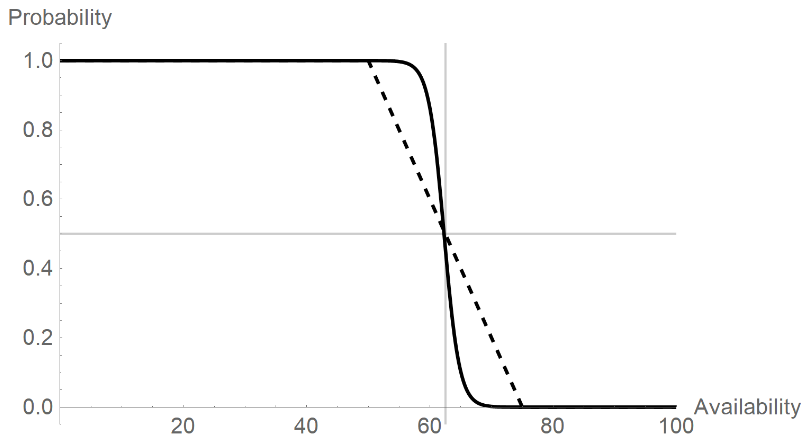

Figure D.9: Turning points of infrastructure[3]

D.5 Findings

An examination of different critical thresholds with respect to the considered cases makes it possible to analyse the overall condition of a system state of waterways as well as the potential criticality of different routes. Thus, in the case under consideration, 25% (62.5%; 100%; 100%) of the cases operate below a critical threshold of 50% (95%; 99%; 100%).

[3] Determining probability of relocation as function of transport costs and aligned utility function for $\alpha = -50$, $\beta = 0.8$, $\Theta = 2$, $\Delta c_s = 2$, $\Delta c_{R_0} = 100\%$, revealing a turning point at A $= 62.5$, in accordance with case 5.

The more detailed comparison of the evaluated availability with the probability to relocate (Figure D.8) shows similar curves which differ in terms of slope and intersection with the 50% probability of relocation as a proxy turning point. This demonstrates the strong interdependence of infrastructure elements on single routes, depicted as scenarios.

For example, case 8 (Figure D.8, bottom right, dashed) and the corresponding route show no (current) criticality since the recent availability is comparatively high and the probability of relocation only becomes relevant once a significantly lower availability threshold is reached.

Case 5 (Figure D.8, bottom left, lined), in contrast, exhibits ranges of similar curves, while the currently assessed availability deviates strongly from that of case 8. Affected locations run the risk of provoking relocation if the availability of the infrastructure is not increased, anticipating the scenario of lowest relocation costs (100%) in this case.

Case 6 (Figure D.8, bottom left, dashed), moreover, highlights that the current availability (45.88%) is not sufficient to enhance local business activities, even within the scenario of the highest relocation costs.

Similarly, case 1 indicates an urgent potential for action since the probability of relocation becomes decisive from an availability of 86.28% (case 6: 90.87%), whereas the current availability is assessed to be below that threshold 77.20%.

Meanwhile, case 3 shows no criticality potential at all since the low cost increase for unavailable infrastructure elements on the route is not decisive for our considered ranges of relocation costs.

Furthermore, the considerations from Section D.4.3.4 demonstrate that the evaluation of the empirical data can be effectively confronted with a utility assessment from the perspective of companies, thus enabling the derivation of the companies' "threshold of pain" for their (re)location decision.

D.6 Conclusion and Discussion

The findings show that the scenario-based approach is especially relevant for considering frequently used transport routes and examining single infrastructure elements regarding their maintenance priority. If the regarded route is highly frequented, special attention must be paid to its availability and the interaction of the infrastructure elements as well as the alternative routes. Comparing current availability and critical availability thresholds helps to assess the urgency and potential of infrastructural measures and investments.

The presented approach establishes a frequently overlooked link between risk-guided routing decisions on the one hand and infrastructure investment on the other. With this, the derived turning points have important implications for policy-makers - particularly infrastructure providers. This way, the link between infrastructure maintenance and a region's attractiveness and competitiveness for industries is made transparent.

In detail, the applied transport model allows a better understanding of the impact on varying demands on the transportation mode choice and also, the effects on varying lock times and infrastructure failure can be interpreted by decision-makers with this model. Furthermore, the proposed formulation allows decision-makers from the industry to optimize the choice of the exchange port next to the delivery routes, quantities, and the number of used vehicles in each mode. Moreover, other data of stakeholding industries such as the coal or arc and stone industry can be implemented to get insights on the optimal transportation mode choice. This analysis allows decision-makers to give priorities on what locks and bridges have the most decisive impact on costs and emissions in case of failure and allows to answer our first research question (*How can cost increases resulting from unavailable infrastructure elements be assessed?*).

The relocation model itself implies that referring to decreasing availability (since we can answer our research question 2, *How can the current availability be assessed?*), should be examined along neatly defined cause-effect-chains. This is because a thorough understanding of the measures taken by companies as a response to different levels of availability is a prerequisite for effective countermeasures by the public sector. This explicitly includes the targeted maintenance management of the infrastructure.

To conclude, this study provides instructive insights in the interconnections of infrastructure availability, short-term company reactions and strategic options like relocating whole facilities. We examine the *costs of infrastructure availability* to answer our third research question. Finally, we demonstrate the relevance of infrastructure maintenance to enhance business locations by identifying critical availability thresholds. Thus, we address our last research question (*Which decreases in availability will cause relocations*). These thresholds can provide important guidance for infrastructure provider and policy makers who need to know the “economically viable attractiveness” of their infrastructure assets.

We promote further opportunities of applying our approach and to continue in refining the proposed utility functions, e.g. by empirical data about risk perceptions and relocation costs. In the light of our findings, we advocate that infrastructure investments in maintenance of IWT structures should always be analyzed regarding their overall economic impact on business locations. The authors want to thank the partners in the joint research project for Digital and Transport (2018). The project is funded by the security research program (www.sifo.de) of the German Federal Ministry of Education and Research (BMBF; grant number 13N14697).

References

Ahmed, K., Bhattacharya, M., Qazi, A. Q., Ghumro, N. A. (2021). Transport Infrastructure and Industrial Output in Pakistan: An Empirical Investigation. *Research in Transportation Economics*, *154*(3), 101040.

An, S., Cui, N., Bai, Y., Xie, W., Chen, M., Ouyang, Y. (2015). Reliable Emergency Service Facility Location under Facility Disruption, En-Route Congestion and In-Facility Queuing. *Transportation Research Part E: Logistics and Transportation Review*, *82*, 199–216.

Andronov, A. M., Jurkina, T. (2015). Reliability of Supply Chains in a Random Environment. *Automatic Control and Computer Sciences*, *49*(6), 340–346.

Bak, O. (2018). Supply Chain Risk Management Research Agenda: From a Literature Review to a Call for Future Research Directions. *Business Process Management Journal*, *24*(2), 567–588.

Ballou, R. H. (1968). Dynamic Warehouse Location Analysis. *Journal of Marketing Research*, *5*(3), 271–276.

Barro, R. J., Sala-i Martin, X. (2001). *Economic Growth* (3rd ed.). Cambridge, Mass.: MIT Press.

Bastian, M., Volkmer, M. (1992). A Perfect Forward Procedure for a Single Facility Dynamic Location/Relocation Problem. *Operations Research Letters*, *12*(1), 11–16.

Bensassi, S., Márquez-Ramos, L., Martínez-Zarzoso, I., Suárez-Burguet, C. (2015). Relationship Between Logistics Infrastructure and Trade: Evidence from Spanish Regional Exports. *Transportation Research Part A: Policy and Practice*, *72*, 47–61.

Beuthe, M., Jourquin, B., Geerts, J.-F., Koul à Ndjang' Ha, Christian. (2001). Freight Transportation Demand Elasticities: A Geographic Multimodal Transportation Network Analysis. *Transportation Research Part E: Logistics and Transportation Review*, *37*(4), 253–266.

Binsfeld, T. (2020). *Bi-Objective Green Multimodal Transportation model - A Case Study from the West-German Canal System.* Paris: Optimisation des Systemes Industriels et Logistiques of Universite Paris-Saclay.

Boloori Arabani, A., Farahani, R. Z. (2012). Facility Location Dynamics: An Overview of Classifications and Applications. *Computers & Industrial Engineering*, *62*(1), 408–420.

Borodulina, S., Pantina, T. (2021). Model of Sustainable Economic Development in the Context of Inland Water Transport Management. In V. Murgul V. Pukhkal (Eds.), *International Scientific Conference Energy Management of Municipal Facilities and Sustainable Energy Technologies EMMFT 2019* (Vol. 1258, pp. 806–819). Cham: Springer International Publishing.

Braunscheidel, M. J., Suresh, N. C. (2009). The Organizational Antecedents of a Firm's Supply Chain Agility for Risk Mitigation and Response. *Journal of Operations Management*, *27*(2), 119–140.

Brusset, X., Teller, C. (2017). Supply Chain Capabilities, Risks, and Resilience. *International Journal of Production Economics*, *184*, 59–68.

Bugert, N., Lasch, R. (2018). Effectiveness of Responsive Pricing in The Face of Supply Chain Disruptions. *Computers & Industrial Engineering*, *124*, 304–315.

Button, K. J., Leitham, S., McQuaid, R. W., Nelson, J. D. (1995). Transport and Industrial and Commercial Location. *The Annals of Regional Science*, *29*(2), 189–206.

Canbolat, Y. B., Chelst, K., Garg, N. (2007). Combining Decision Tree and Maut For Selecting a Country for a Global Manufacturing Facility. *Omega*, *35*(3), 312–325.

Carter, C. R., Rogers, D. S., Choi, T. Y. (2015). Toward the Theory of the Supply Chain. *Journal of Supply Chain Management*, *51*(2), 89–97.

Cavalcante, I. M., Frazzon, E. M., Forcellini, F. A., Ivanov, D. (2019). A Supervised Machine Learning Approach to Data-Driven Simulation of Resilient Supplier Selection in Digital Manufacturing. *International Journal of Information Management*, *49*(3), 86–97.

Chand, S. (1988). Decision/Forecast Horizon for a Single Facility Dynamic Location/Relocation Problem. *Operations Research Letters*, *7*(5), 247–251.

Chatti, K., Zaabar, I. (2012). *Estimating The Effects of Pavement Condition on Vehicle Operating Costs* (Vol. 720). Washington, D.C.: Transportation Research Board.

Cheaitou, A., Hamdan, S., Larbi, R., Alsyouf, I. (2020). Sustainable Traveling Purchaser Problem with Speed Optimization. *International Journal of Sustainable Transportation*, *15*, 1–20.

Choi, T.-M. (2021). Risk Analysis in Logistics Systems: A Research Agenda during and after the Covid-19 Pandemic. *Transportation Research Part E: Logistics and Transportation Review*, *145*, 102190.

Chowdhury, P., Paul, S. K., Kaisar, S., Moktadir, M. A. (2021). Covid-19 Pandemic Related Supply Chain Studies: A Systematic Review. *Transportation Research. Part E, Logistics and Transportation Review*, *148*, 102271.

Christopher, M. (2016). *Logistics & Supply Chain Management* (5th ed.). Harlow, United Kingdom: Pearson Education.

Church, R., ReVelle, C. (1974). The Maximal Covering Location Problem. *Papers of the Regional Science Association*, *32*, 101–118.

Cigu, E., Agheorghiesei, D. T., Gavriluță, A. F. G., Toader, E. (2019). Transport Infrastructure Development, Public Performance and Long-Run Economic Growth: A Case Study for the Eu-28 Countries. *Sustainability*, *11*(1), 67.

Coetzee, Petrus J. van V., Swanepoel, P. A. (2017). Spatial Relationships and Movement Patterns of the Air Cargo Industry in Airport Regions. *Journal of Transport and Supply Chain Management*, *11*(0), 10.

Cui, T., Ouyang, Y., Shen, Z.-J. M. (2010). Reliable Facility Location Design Under the Risk of Disruptions. *Operations Research*, *58*(4-part-1), 998–1011.

Current, J., Daskin, M., Schilling, D. (2002). Discrete Network Location Models. *Facility location: Applications and theory*, *1*, 81–118.

Daskin, M. S. (2011). *Network and discrete location: Models, algorithms, and applications*. John Wiley & Sons.

de Bok, M. (2009). Estimation and Validation of a Microscopic Model for Spatial Economic Effects of Transport Infrastructure. *Transportation Research Part A: Policy and Practice*, *43*(1), 44–59.

DIN. (2013). *Din 16258: Methodology for Calculation And Declaration of Energy Consumption and GHG Emissions of Transport Services (Freight and Passengers)* (No. 16258:2013-03). Berlin: Beuth Verlag GmbH.

Dolgui, A., Ivanov, D., Sokolov, B. (2018). Ripple Effect in the Supply Chain: An Analysis and Recent Literature. *International Journal of Production Research*, *56*(1-2), 414–430.

Doorly, V. B. (2020). *Megatrends Defining The Future Of Tourism* (Vol. 6). Springer.

Drezner, T. (2014). A Review of Competitive Facility Location in the Plane. *Logistics Research*, *7*(1).

Essen, H., Fiorello, D., El Beyrouty, K., Bieler, C., Wijngaarden, L., Schroten, A., . . . Fermi, F. (2020). *Handbook on the External Costs Of Transport : Version 2019 - 1.1*. Publications Office.

European Court of Auditors. (2015). *Inland Waterway Transport in Europe: No Significant Improvements in Modal Share and Navigability Conditions Since 2001*. Luxembourg: Publications Office of the European Union.

Eusgeld, I., Nan, C., Dietz, S. (2011). "System-of-Systems" Approach for Interdependent Critical Infrastructures. *Reliability Engineering & System Safety*, *96*(6), 679–686.

Faertes, D. (2015). Reliability of Supply Chains and Business Continuity Management. *Procedia Computer Science*, *55*, 1400–1409.

Farahani, R. Z., Drezner, Z., Asgari, N. (2009). Single Facility Location and Relocation Problem with Time Dependent Weights and Discrete Planning Horizon. *Annals of Operations Research*, *167*(1), 353–368.

Federal Statistical Office of Germany (Ed.). (2019). Verkehr: Güterverkehrsstatistik der Binnenschifffahrt. , *4*(8).

Feng, X., Hu, S., Gu, W., Jin, X., Lu, Y. (2020). A Simulation-Based Approach for Assessing Seaside Infrastructure Improvement Measures for Large Marine Crude Oil Terminals. *Transportation Research Part E: Logistics and Transportation Review*, *142*, 102051.

Fujita, M., Thisse, J.-F. (2006). Globalization And The Evolution Of The Supply Chain: Who Gains And Who Loses? *International Economic Review*, *47*(3), 811–836.

Gast, J., Wehrle, R. (2019). Application of the Concept of Supply Chain Reliability for an Availability Assessment of Inland Waterway Systems.

Gast, J., Wehrle, R., Wiens, M., Schultmann, F. (2020). Impact of Notification Time on Risk Mitigation in Inland Waterway Transport. *Hamburg International Conference of Logistics (HICL)*(2020).

Gherghina, Ş., Onofrei, M., Vintilă, G., Armeanu, D. (2018). Empirical Evidence from EU-28 Countries on Resilient Transport Infrastructure Systems and Sustainable Economic Growth. *Sustainability*, *10*(8), 2900.

Gu, Y., Fu, X., Liu, Z., Xu, X., Chen, A. (2020). Performance of Transportation Network under Perturbations: Reliability, Vulnerability, And Resilience. *Transportation Research Part E: Logistics and Transportation Review*, *133*, 101809.

Hajibabai, L., Bai, Y., Ouyang, Y. (2014). Joint Optimization of Freight Facility Location and Pavement Infrastructure Rehabilitation under Network Traffic Equilibrium. *Transportation Research Part B: Methodological*, *63*, 38–52.

Hakimi, S. L. (1964). Optimum Locations of Switching Centers and the Absolute Centers and Medians of a Graph. *Operations Research*, *12*(3), 450–459.

Heckmann, I., Comes, T., Nickel, S. (2015). A Critical Review on Supply Chain Risk – Definition, Measure and Modeling. *Omega*, *52*(1), 119–132.

Helm, D. (2020). The Environmental Impacts of the Coronavirus. *Environmental & Resource Economics*, *76*, 1–18.

Hintjens, J., van Hassel, E., Vanelslander, T., van de Voorde, E. (2020). Port Cooperation and Bundling: A Way to Reduce the External Costs of Hinterland Transport. *Sustainability*, *12*(23), 9983.

Hong, J., Chu, Z., Wang, Q. (2011). Transport Infrastructure and Regional Economic Growth: Evidence from China. *Transportation*, *38*(5), 737–752.

Hormozi, A. M., Khumawala, B. M. (1996). An Improved Algorithm for Solving a Multi-Period Facility Location Problem. *IIE Transactions*, *28*(2), 105–114.

Hosseini, S., Ivanov, D., Dolgui, A. (2019). Review of Quantitative Methods for Supply Chain Resilience Analysis. *Transportation Research Part E: Logistics and Transportation Review*, *125*, 285–307.

Ivanov, D. (2020). Viable Supply Chain Model: Integrating Agility, Resilience and Sustainability Perspectives-Lessons From and Thinking Beyond the COVID-19 Pandemic. *Annals of Operations Research*, 1–21.

Jetlund, A. S., Karimi, I. (2004). Improving the Logistics of Multi-Compartment Chemical Tankers. *Computers & Chemical Engineering*, *28*(8), 1267–1283.

Jiang, Y., Timmermans, H. J., Yu, B. (2018). Relocation of Manufacturing Industry from the Perspective of Transport Accessibility - An Application of Percolation Theory. *Transport Policy*, *63*, 10–29.

Ke, G. Y., Verma, M. (2021). A Framework to Managing Disruption Risk in Rail-Truck Intermodal Transportation Networks. *Transportation Research Part E: Logistics and Transportation Review*, *153*, 102340.

Kotowska, I., Mańkowska, M., Pluciński, M. (2018). Inland Shipping to Serve the Hinterland: The Challenge for Seaport Authorities. *Sustainability*, *10*(10), 3468.

Kwon, J., Barkley, T., Hranac, R., Petty, K., Compin, N. (2011). Decomposition of Travel Time Reliability into Various Sources. *Transportation Research Record: Journal of the Transportation Research Board*, *2229*(1), 28–33.

Lambiase, A., Mastrocinque, E., Miranda, S., Lambiase, A. (2013). Strategic Planning and Design of Supply Chains: A Literature Review. *International Journal of Engineering Business Management*, *5*, 49.

Li, G., Zhang, L., Guan, X., Zheng, J. (2016). Impact Of Decision Sequence On Reliability Enhancement With Supply Disruption Risks. *Transportation Research Part E: Logistics and Transportation Review*, *90*(1), 25–38.

Li, S., Cai, J., Feng, Z., Xu, Y., Cai, H. (2019). Government Contracting with Monopoly in Infrastructure Provision: Regulation or Deregulation? *Transportation Research Part E: Logistics and Transportation Review*, *122*, 506–523.

Lim, M. K., Bassamboo, A., Chopra, S., Daskin, M. S. (2013). Facility Location Decisions with Random Disruptions and Imperfect Estimation. *Manufacturing & Service Operations Management*, *15*(2), 239–249.

Linnenluecke, M. K. (2017). Resilience in Business and Management Research: A Review of Influential Publications and a Research Agenda. *International Journal of Management Reviews*, *19*(1), 4–30.

MacKenzie, C. A., Barker, K., Grant, F. H. (2012). Evaluating the Consequences of an Inland Waterway Port Closure with a Dynamic Multiregional Interdependence Model. *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, *42*(2), 359–370.

Manfredi, S., Di Tucci, E., LATORA, V. (2018). Mobility and Congestion in Dynamical Multilayer Networks with Finite Storage Capacity. *Physical Review Letters*, *120*(6), 068301.

McCalla, R. J., Slack, B., Comtois, C. (2001). Intermodal Freight Terminals: Locality and Industrial Linkages. *The Canadian Geographer/Le Géographe canadien*, *45*(3), 404–413.

Mejia-Dorantes, L., Paez, A., Vassallo, J. M. (2012). Transportation Infrastructure Impacts on Firm Location: The Effect of a New Metro Line in the Suburbs of Madrid. *Journal of Transport Geography*, *22*, 236–250.

Melo, M. T., Nickel, S., Saldanha-da Gama, F. (2009). Facility Location and Supply Chain Management - a Review. *European Journal of Operational Research*, *196*(2), 401–412.

Mentzer, J. T., DeWitt, W., Keebler, J. S., Min, S., Nix, N. W., Smith, C. D., Zacharia, Z. G. (2001). Defining Supply Chain Management. *Journal of Business Logistics*, *22*(2), 1–25.

Mohammadi, M., Jula, P., Tavakkoli-Moghaddam, R. (2019). Reliable Single-Allocation Hub Location Problem with Disruptions. *Transportation Research Part E: Logistics and Transportation Review*, *123*, 90–120.

Munich Re. (2018). *Topics Geo Naturkatastrophen 2017: Analysen, Bewertungen, Positionen.* München: Gotteswinter und Aumaier GmbH.

Nozick, L. K. (2001). The Fixed Charge Facility Location Problem with Coverage Restrictions. *Transportation Research Part E: Logistics and Transportation Review*, *37*(4), 281–296.

Oztanriseven, F., Nachtmann, H. (2020). Modeling Dynamic Behavior of Navigable Inland Waterways. *Maritime Economics & Logistics*, *22*(2), 173–195.

Pant, R., Barker, K., Landers, T. L. (2015). Dynamic Impacts of Commodity Flow Disruptions in Inland Waterway Networks. *Computers & Industrial Engineering*, *89*(2), 137–149.

Pradhan, R. P. (2019). Investigating the Causal Relationship between Transportation Infrastructure, Financial Penetration and Economic Growth in G-20 Countries. *Research in Transportation Economics*, *78*(C), 100766.

Qazi, A., Quigley, J., Dickson, A., Ekici, Ş. Ö. (2017). Exploring Dependency Based Probabilistic Supply Chain Risk Measures for Prioritising Interdependent Risks and Strategies. *European Journal of Operational Research*, *259*(1), 189–204.

Rezaei, J., van Roekel, W. S., Tavasszy, L. (2018). Measuring the Relative Importance of the Logistics Performance Index Indicators using Best Worst Method. *Transport Policy*, *68*, 158–169.

Seyedhosseini, S. M., Makui, A., Shahanaghi, K., Torkestani, S. S. (2016). Models, Solution, Methods and their Applicability of Dynamic Location Problems (DLPS) (A Gap Analysis for Further Research). *Journal of Industrial Engineering International*, *12*(3), 311–341.

Shukla, V., Waddell, P. (1991). Firm Location and Land use in Discrete Urban Space: A Study of the Spatial Structure of Dallas-Fort Worth 0. *Regional Science and Urban Economics*, *21*(2), 225–253.

Snyder, L. V., Atan, Z., Peng, P., Rong, Y., Schmitt, A. J., Sinsoysal, B. (2016). OR/MS Models for Supply Chain Disruptions: A Review. *IIE Transactions*, *48*(2), 89–109.

Snyder, L. V., Daskin, M. S. (2005). Reliability Models for Facility Location: The Expected Failure Cost Case. *Transportation Science*, *39*(3), 400–416.

Stewart, M. G., Wang, X., Nguyen, M. N. (2011). Climate Change Impact and Risks of Concrete Infrastructure Deterioration. *Engineering Structures*, *33*(4), 1326–1337.

Strauss-Kahn, V., Vives, X. (2009). Why And Where do Headquarters Move? *Regional Science and Urban Economics*, *39*(2), 168–186.

Sullivan, J. L., Novak, D. C., Aultman-Hall, L., Scott, D. M. (2010). Identifying Critical Road Segments and Measuring System-Wide Robustness in Transportation Networks with Isolating Links: A Link-Based Capacity-Reduction Approach. *Transportation Research Part A: Policy and Practice*, *44*(5), 323–336.

Sweeney, D. J., Tatham, R. L. (1976). An Improved Long-Run Model for Multiple Warehouse Location. *Management Science*, *22*(7), 748–758.

Sys, C., van de Voorde, E., Vanelslander, T., van Hassel, E. (2020). Pathways for a Sustainable Future Inland Water Transport: A Case Study for the European Inland Navigation Sector. *Case Studies on Transport Policy*, *8*(3), 686–699.

Taghizadeh, H., Hafezi, E. (2012). The Investigation of Supply Chain's Reliability Measure: A Case Study. *Journal of Industrial Engineering International*, *8*(1), 1–10.

Tang, C. S. (2006). Robust Strategies for Mitigating Supply Chain Disruptions. *International Journal of Logistics Research and Applications*, *9*(1), 33–45.

Tapiero, C. S. (1971). Transportation-Location-Allocation Problems over Time. *Journal of Regional Science*, *11*(3), 377–384.

Tavasszy, L. A., Ruijgrok, K., Davydenko, I. (2012). Incorporating Logistics in Freight Transport Demand Models: State-of-the-Art and Research Opportunities. *Transport Reviews*, *32*(2), 203–219.

The World Bank. (2018). *Connecting to Compete 2018: Trade Logistics in the Global Economy: The Logistics Performance Index and Its Indicators*. Washington, D.C..

Tomlin, B. (2006). On the Value of Mitigation and Contingency Strategies for Managing Supply Chain Disruption Risks. *Management Science*, *52*(5), 639–657.

Trucco, P., Petrenj, B. (2017). Resilience of Critical Infrastructures: Benefits and Challenges from Emerging Practices and Programmes at Local Level. In I. Linkov J. M. Palma-Oliveira (Eds.), *Resilience and risk* (pp. 225–286). Dordrecht: Springer.

van de Vooren, F. (2004). Modelling Transport in Interaction with The Economy. *Transportation Research Part E: Logistics and Transportation Review*, *40*(5), 417–437.

van Hassel, E., VaneIslander, T., Doll, C. (2018). *Working Paper 7: The Assessment of Different Future Freight Transport Scenarios for Europe and the North Rhine-Westphalia Region: Study Lowcarb-Rfc - European Rail Freight Corridors Going Carbon Neutral.*

Wagner, S. M., Bode, C. (2006). An Empirical Investigation Into Supply Chain Vulnerability. *Journal of Purchasing and Supply Management*, *12*(6), 301–312.

Wehrle, R., Gast, J., Wiens, M., Schultmann, F. (2022). On the Influence of Infrastructure Availability on Companies Decisions towards Modal Shift and Relocation of Facilities.

Wehrle, R., Wiens, M., Schultmann, F., Akkermann, J., Bödefeld, J. (2020). Ebenensystem zur Resilienzbewertung kritischer Verkehrsinfrastrukturen am Beispiel der Wasserstraßen. *Bautechnik*, *97*(6), 395–403.

Wesolowsky, G. O. (1973). Dynamic Facility Location. *Management Science*, *19*(11), 1241–1248.

Wesolowsky, G. O., Truscott, W. G. (1975). The Multiperiod Location-Allocation Problem with Relocation of Facilities. *Management Science*, *22*(1), 57–65.

Wiegmans, B., Konings, R. (2015). Intermodal Inland Waterway Transport: Modelling Conditions Influencing Its Cost Competitiveness. *The Asian Journal of Shipping and Logistics*, *31*(2), 273–294.

Witt, M. A. (2019). De-Globalization: Theories, Predictions, and Opportunities for International Business Research. *Journal of International Business Studies*, *50*(7), 1053–1077.

World Economic Forum. (2021). *The Global Risks Report 2021.* Cologny/Geneva.

Wu, T., Blackhurst, J., O'grady, P. (2007). Methodology for Supply Chain Disruption Analysis. *International Journal of Production Research*, *45*(7), 1665–1682.

Yamada, T., Febri, Z. (2015a). Freight Transport Network Design Using Particle Swarm Optimisation in Supply Chain - Transport Supernetwork Equilibrium. *Transportation Research Part E: Logistics and Transportation Review*, *75*, 164–187.

Yamada, T., Febri, Z. (2015b). Freight Transport Network Design Using Particle Swarm Optimisation in Supply Chain–Transport Supernetwork Equilibrium. *Transportation Research Part E: Logistics and Transportation Review*, *75*, 164–187.

Yu, H., Zeng, A. Z., Zhao, L. (2009). Single or Dual Sourcing: Decision-Making in the Presence of Supply Chain Disruption Risks. *Omega*, *37*(4), 788–800.

Zepeda Ortega, I. E., Ángeles-Castro, G., Carrillo-Murillo, D. G. (2019). Road Infrastructure and Economic Growth in Mexico. *Problemas del Desarrollo. Revista Latinoamericana de Economía*, *50*(198).

Zhang, Y., Snyder, L. V., Ralphs, T. K., Xue, Z. (2016). The Competitive Facility Location Problem under Disruption Risks. *Transportation Research Part E: Logistics and Transportation Review*, *93*, 453–473.

E Application of collaborative serious gaming for the elicitation of expert knowledge and towards creating situation awareness in the field of infrastructure resilience

Abstract[1]

Increasing ageing of transport infrastructures requires a systematic resilience-based maintenance strategy. However, the assessment of risk and resilience is problematic due to the manifold influencing factors and mechanisms within the complex socio-technical system of infrastructure maintenance. This paper provides an analysis of the intricate processes and interdependencies, which influence the potential for resilient infrastructure maintenance. The presented iterative framework incorporates the elicitation of expert knowledge and a serious gaming application. Providing a valid environment for a systematic and guided dialogue among decision makers, serious gaming is highlighted as a valuable research tool that can effectively increase stakeholders' Situation Awareness and thus improve infrastructure resilience itself and its assessment. The authors developed a collaborative board game which emulates real-life decisions of stakeholders in the context of German waterways. In particular, the interaction of the players who take specific stakeholder roles contribute to a deeper understanding of the system, including the impacts of the players' decisions in the realworld system. The paper shows the contribution and potential of serious gaming, including a proposed integration into a Bayesian network as resilience assessment tool. It becomes obvious that the exploitation of expert knowledge to the end of improved systemic decision making requires that the application is closely aligned with the real-world system and the research method in all phases of gamification. On overall, the insights of this study suggest that serious collaborative gaming should be considered more in both research and practice, thus creating Situation Awareness among stakeholders of critical infrastructures (CI).

[1] This chapter includes the preprint of the article "Application of collaborative serious gaming for the elicitation of expert knowledge and towards creating situation awareness in the field of infrastructure resilience" by Marcus Wiens, Frank Schultmann, and myself (Wehrle et al., 2021).

Keywords: Serious Game; Cooperative Gaming; Expert Knowledge; Resilience; Complex Systems

E.1 Introduction

Infrastructure systems form the backbone of modern civilization. They represent large socio-technical systems in society, which contribute to the supply and distribution of services, materials, and assets to households, companies, and organizations. Therefore, they have to fulfill a service quality which requires, among others, reliability and accessibility (Johansson et al., 2007). If infrastructure failure bears the potential to lead to dramatic consequences in terms of a disruption of essential services, the term Critical Infrastructure (CI) is used (Federal Ministry of the Interior and Community, 2009; Rinaldi et al., 2001).

A key infrastructure component in this respect is the transport infrastructure, as it enables the mobility of people and the supply of goods. However, examinations of transport infrastructure reveal that the stock of physical assets is often ageing faster than maintenance is performed, which endangers the fulfillment of their service quality (Federal Ministry for Digital and Transport, 2019; Žnidarič et al., 2011; Panenka et al., 2020). These developments entail that maintenance work is predominantly carried out on an as-needed basis running behind the problems and leaving an ageing infrastructure which runs the risk of disruption and failure of its function, endangering CI protection (Francis and Bekera, 2014; Gay and Sinha, 2012; Alcaraz and Zeadally, 2015).

Instead, a proactive maintenance strategy is important which should be anticipatory as well as risk- and resilience-oriented to become robust against sudden disruptions (Ayyub, 2014). A resilience-based maintenance strategy can optimize the allocation of scarce human and monetary resources toward ensuring the infrastructure's resilience. However, this ultimately requires a resilience assessment taking into account manifold system characteristics (Bocchini et al., 2014).

Maintenance strategies and resilience assessments should particularly take into consideration the stakeholders involved and their interactions (Francis and Bekera, 2014) since usage and governance of the infrastructure strongly depends on human and societal factors. A system-wide understanding of the interdependencies of infrastructures as complex interconnected system-of-systems is required, revealing the need to elicit and include stakeholder knowledge in the process of understanding the systems. For example, the transport infrastructure is embedded into global and local supply chains where final customers and pre-processing industries depend on a smooth and reliable transportation flow. Hence, for both resilience assessment and enhanced Situation Awareness it is necessary to consider transport infrastructure not only as an isolated system but as complex system which is characterized by interdependencies to other infrastructures (Rinaldi et al., 2001). Moreover, infrastructures represent system-of-systems which represent large scale concurrent and distributed systems whose components are complex systems themselves (Eusgeld et al., 2011; Kotov, 1997).

In addition to the system-of-systems-perspective on infrastructure, key decision-makers need to understand their own role together with the role and objectives of co-decision-makers they are closely linked and who have a significant impact on overall performance. This requires Situation Awareness (Endsley, 1995) by all stakeholders who are involved as decision-makers, since a shared awareness of a collective system improves its resilience (Craighead et al., 2007). Overall, timely and trusted information sharing and collaboration among stakeholders are crucial within CI protection (Department of Homeland Security, 2016). Hence, both from the perspective of the infrastructure operators and other stakeholders involved, it is important to have a good understanding of one's own role as well as the interdependencies. However, due to the complexity of the system-of-systems and lack of exchange, this is rarely possible.

A promising approach to overcome this problem is Serious Gaming (SG). SG is a method that has become increasingly popular in recent years (Kasurinen and Knutas, 2018). This method offers the advantage that stakeholders have to solve a problem together, i.e. cooperatively and interactively. Static knowledge plays a less important role here than process-oriented learning, which leads to a better understanding of the problem and thus to more promising approaches to solving it (Wouters et al., 2009, 2013).

The aim of this paper is to address both of these objectives by the use of SG as a tool to elicitate experts' knowledge and simultaneously serving as an exercise for stakeholders to enhance their Situation Awareness as decision-makers and to evaluate the potential and limits of gamification towards the objectives. In detail, this contribution pursues two objectives with the use of SG: First, we use SG as a tool for the elicitation of interdisciplinary expertise. As this knowledge is provided during a game play, the reported experience goes beyond the invidual, isolated perspective. This way, collaborative stakeholder inquiry leads to a higher level of external validity and thus to a more robust resilience assessment. Second, being involved in a game strengthens the stakeholders' Situation Awareness and thus explicitly improves the knowledge and insights of system-relevant decision makers which lays the foundation for more informed decision-making.

The paper is structured as follows: An iterative framework towards assessing resilience of infrastructure systems as complex systems is provided and the role of expert knowledge and of Situation Awareness are introduced within the context of a resilience-based maintenance strategy of transport infrastructure (Section E.2.1). In Section E.2.2, we introduce the method of Serious Gaming and discuss possible contributions to research purposes and resilience enhancement before we analyse existing applications and game design principles. Afterwards, the serious game approach is applied to the case of German inland waterways in Section E.3. The procedure together with the key findings are described in detail in Section E.5.

E.2 Method

E.2.1 Maintenance of Critical Infrastructure

The following sub-sections describe a general framework towards assessing resilience and emphasize the roles of both expert knowledge and Situation Awareness before we establish the methodological nexus to Serious Gaming.

E.2.1.1 Transport infrastructure as a complex system

Infrastructures represent complex systems and can be regarded as system-of-systems with complex sub-systems and interdependencies, playing a fundamental role in their understanding (Rinaldi et al., 2001; Eusgeld et al., 2011; Haimes, 2018). According to Haimes (2018), the observation of infrastructures as a complex system results, among others, from the following characterizing components: (i) states, which constitute the fundamental entities of all systems; (ii) decision-makers and stakeholders; (iii) resources; (iv) organizational setups; (v) emergent behavior and evolution; (vi) often competing and conflicting goals and objectives; and (vii) historical and cultural identity, and time frame.

Understanding transportation infrastructure as a complex system is especially important when examining corresponding risks and resilience capacities, as it requires diversified modeling perspectives and innovative analysis approaches (Zio, 2016).

E.2.1.2 Resilience-based maintenance of transport infrastructure

Overall, a structured analysis of transport infrastructures is needed and can be ensured by an iterative step-by-step approach which is reflected by the structure of the paper and illustrated by Figure E.1. This general research framework considers (1) the understanding of the problem, which includes a thorough understanding of the problem as need for resilience assessment, the collection of basic data such as the identification of general system properties and possible resolution levels. The evaluation of suitable methods must account for the specifications of the system and of the analysed problem.

Data collection and analysis (2) include the transfer aspects of the real world into a modeling environment which is followed by an iterative process. This includes a reflection phase after (3) the assessment based on key-figures to extend data collection and analysis and end with the last iteration leading to (4) the conclusion of results. This approach ensures a problem-oriented analysis, considers different stages and depths of data collection and analysis as well as a continuous refinement of scientific models.

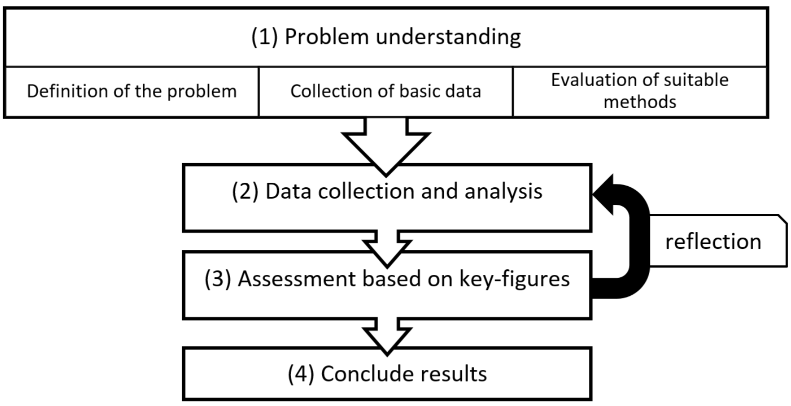

Figure E.1: Iterative Step-by-step approach towards system analysis

Special requirements for a resilience assessment of transport infrastructures arise primarily by their nature of being a complex system which induce characteristics namely referring to its adaptability, self-organization, stability, cumulative character and possible phase transitions (Rodrigue, 2020). The network character of complex interdependencies with other infrastructures and responsibilities which are necessary to provide optimal performance (Rinaldi et al., 2001) lead to further challenges for a reliable resilience assessment and analysis. While these interdependencies are a characteristic feature of modern, high-performance infrastructure networks optimized for synergies, they also increase the vulnerability of a system (Ouyang, 2014) and can lead to serious cascading failures (Shin et al., 2018).

Resilience-based maintenance strategies require the assessment of resilience which describes the ability of systems to cope with a sudden disruption and its ability to restore its operability (Ayyub, 2014; Jüpner et al., 2018). Literature provides a broad range of methods for assessing the resilience of infrastructures such as empirical, agent based, network based, system dynamics based and economic theory based approaches (cf. e.g. Ouyang, 2014; Argyroudis et al., 2019). Since for the analysis of infrastructure resilience (1) uncertainties about the availability and (2) interdependencies of CIs systems are central,

Bayesian networks are among the most promising approaches for such type of analysis. To cope with the complexity of the interdependencies and cascading effects, the application of Bayesian networks contributes to an uncertainty-based modeling of interdependent infrastructures. Nevertheless, this particular area of application is rather scarce in the literature (Hosseini and Barker, 2016; Tang et al., 2020).

Possible influencing factors of infrastructure resilience are identified by Hosseini and Barker (2016). The authors address three established types of resilience capacities as part of the resilience definition: Absorptive capacity refers to the robustness of a system against the impact of disruptive events. Adaptive capacity includes temporary solutions to recover, while restorative capacity refers to permanent activities to restore damaged infrastructure from disruptions (Hosseini and Barker, 2016).

The first research objective (contributing to a robust resilience assessment) will be addressed in this paper through data analysis within the Bayesian network framework and validation of the systemic interrelationships. Moreover, the second research goal (strengthen Situation Awareness) is explicitly targeted via the feedback loop, which is intended to increase the experts' knowledge and insights.

E.2.1.3 The role of expert knowledge

As in almost every research area, the inclusion of expert knowledge is indispensable for resilience assessment, since expert judgement can be seen as a specific form of scientific data (Cooke and Goossens, 2004). Insights from the contributory expertise of experts can be used in phase (1) and (2) of the depicted framework (Figure E.1) and can be linked with the in-depth analysis of empirical data as well as being addressed explicitly by the process of Bayesian inference as stated before Panenka et al. (2020); Box and Tiao (1992).

The described problem concerns a complex system, which is why the collection of input data and insufficient availability of data due to limited possibilities for data collection can be constraining factors. As a consequence, expert knowledge must be considered and incorporated as broadly as possible and in reasonable depth. In particular, a reliable application of Bayesian networks to assess infrastructure resilience requires specific knowledge about external circumstances and internal processes which can best be contributed by experts (Hosseini and Barker, 2016).

Since experts can be researchers who have specialized knowledge as well as stakeholders of a considered CI, relevant experts must be first identified (Reed et al., 2009). To elaborate relevant stakeholders it is essential to consider that the value of an infrastructure is significantly linked to its economic function (Johansson et al., 2007). In the case of transport infrastructure elements, the economic function refers primarily to the function of freight transport revealing industries as key stakeholders, which are responsible for the production and transportation of goods. Further stakeholders and resources are needed to ensure functionality and availability of the infrastructure through maintenance and repair. These include primarily the infrastructure investor and the operator, usually represented by one or more public authorities. Available resources moreover concern money and time as well as the responsibility for employees.

Procedures need to be identified to enhance the understanding that the various stakeholders' decisions influence each other and the manner in which they affect each other. For example, it is important for an industrial operator to have knowledge about the level of availability of a transport infrastructure to maintain its production (Gast and Wehrle, 2019). Low availability leads to a shift of capacity to other modes of transport or even to other locations. This in turn affects the revenue of the infrastructure operator in the form of user fees as well as the state in the form of tax revenue. The state, in turn, is responsible for ensuring a certain level of availability of transport infrastructure by coordinating resources and measures which it allocates towards specific projects. Thus, for a deeper understanding of these interconnections, decisions, as well as their impact on resilience, stakeholder knowledge needs to be incorporated into the data collection process and can be explicitly addressed by the application of Bayesian networks.

Expert knowledge must be elicited and used in an efficient process to serve the research target in a reliable way, including the consideration of the possibility of cognitive or motivational bias by the concept and methods (Miles et al., 2020). The spectrum of possible methodologies ranges from observations and direct interviews over process tracing up to conceptual techniques (Cooke, 1994). Furthermore, environments in which expert knowledge is gained must fulfil a claim for validity to enable trustworthy intuitions of experts to be observed (Kahneman and Klein, 2009).

Structured expert interviews can contribute predominantly to the problem understanding and first step of data collection and analysis which can lead towards a first assessment based on key-figures. For a next iteration of these steps (Figure E.1), the knowledge acquired by then can be addressed by further targeted techniques.

E.2.1.4 The role of Situation Awareness for resilient transport infrastructure as a complex system

Beyond contributing to the assessment of resilience, the inclusion of experts can simultaneously lead to an increase in resilience since awareness among stakeholders influences their decision making. Situation Awareness as important precondition for informed decision making is defined as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (Endsley, 1995). It is based on the perception of relevant parameters of the surrounding system and comprises spatial awareness, system awareness, and task awareness (Endsley, 1995; Wickens, 2002).

The inclusion of system awareness reveals that beyond the focus on the near future in the stated definition, systemic interrelations are highly influencing awareness, decisions and therefore systemic performance (Figure E.2) and resilience. Regarding CI protection, the systemic relationship between its resilience and availability on the one hand and the additional value generated or damage avoided in the long term on the other is of particular importance (Alcaraz and Zeadally, 2015).

Situation Awareness among decision-makers leads to better-informed decisions that consider system-wide consequences. Therefore it can significantly contribute to improved resilience by supporting a shared awareness of a collective system (Craighead et al., 2007), among others by continuously improving systems (Ouyang, 2014).

Factors influencing Situation Awareness within a system are individual goals, objectives, and expectations, which are directly influenced by individual skills, experience, and training, which also have a direct impact on Situation Awareness, decisions and performance (Endsley, 1995). As a result, individual factors should be operationalized to promote Situation Awareness.

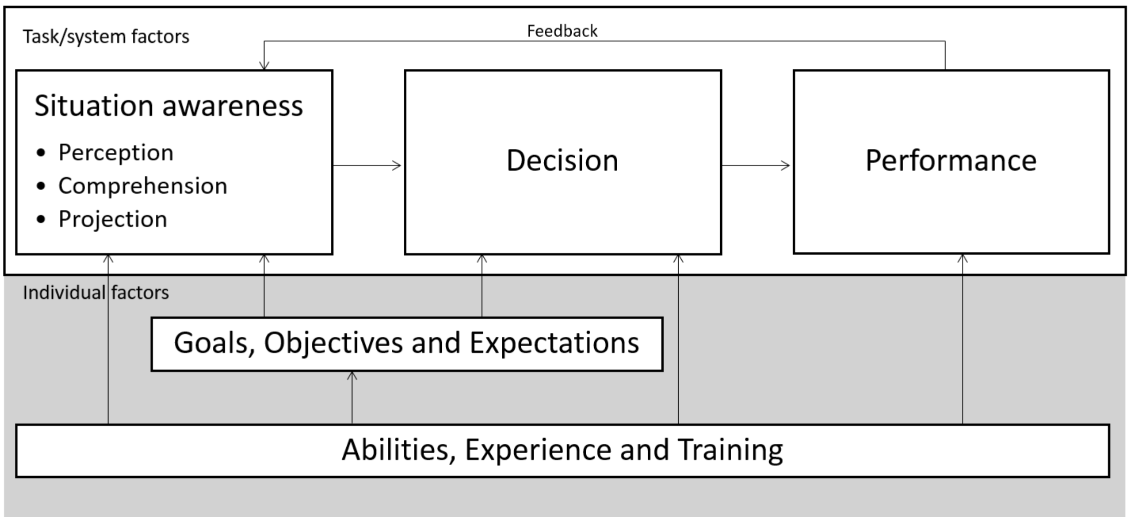

Figure E.2: Situation Awareness and decision making
(Endsley, 1995)

E.2.2 Integration of experts using Serious Gaming

The previous considerations can be addressed by Serious Gaming, as it is able to satisfy both the need for extracting and incorporating expert knowledge (Section E.2.1.3) and the need for strengthening Situation Awareness (Section E.2.1.4) to increase infrastructure resilience.

The term Serious Gaming refers to games with an explicit purpose which are used within various fields (Abt, 1970; Alvarez and Djaouti, 2011; Crookall, 2010). Serious Gaming combines game technology with science in real-world fields of applications, whereas the explicit purpose of a serious game can be, for example, the analysis of human behavior, to achieve a training effect in the skills of the players (Rüppel and Schatz, 2011) or to develop a better understanding and increased awareness of complex issues and interdependencies in complex systems (Lukosch et al., 2018).

Figure E.3 shows how the objectives are pursued by a Serious Gaming approach, including the elements of Game Design and its application (further elaborations in Section E.2.3), whereas the targeting of the purposes ensues in the following.

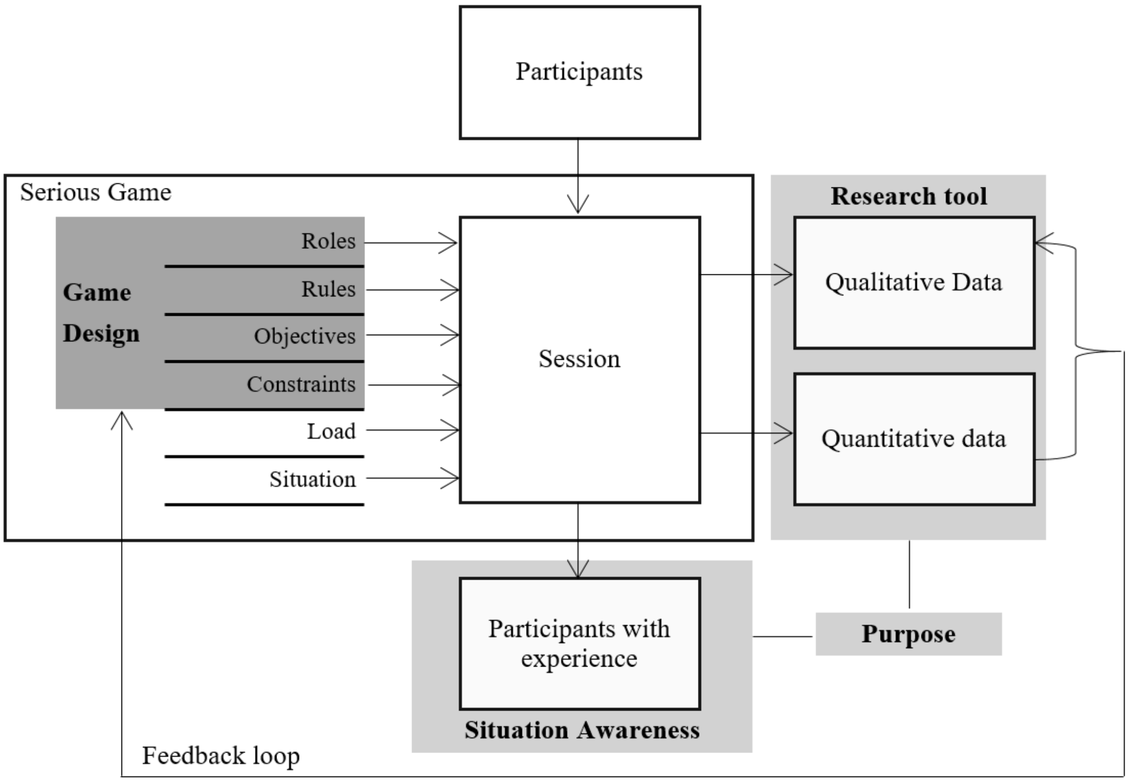

Figure E.3: Inputs and Outputs of Serious Gaming
(Meijer, 2009)

E.2.2.1 Serious Gaming as method to elicitate expert knowledge

In research, serious games can be used to test models in simulated environments by emphasizing theories about the systems' interdependencies to analyse various solutions in alternative constellations. The players, referred to as participants in Figure E.3, are enhanced to learn the logic of the simulated processes by participating and observing the consequences of their decisions (Abt, 1970). Serious Gaming can therefore contribute to examine motivations behind real-world decisions of stakeholders (Fleming et al., 2020).

Freese et al. (2020) identify serious games as valuable research instruments since they provide controllable and safe environments, allowing both for exploration and observation of stakeholder behaviour and decision-making processes. Therefore, they are able to provide a "high-validity" environment as required by Kahneman and Klein (2009) (cf. Section E.2.1.3).

Serious Gaming can furthermore be used as a tool for hypothesis testing, with a set of induced hypotheses being an important byproduct of the game design phase (Meijer, 2009). Qualitative and quantitative data can be gained by observing and evaluating game sessions and can be used in a feedback loop to customize the game design for individual analysis (Meijer, 2009), as depicted in Figure E.3. Thus, Serious Gaming can be seen as a valuable tool to elicit expert knowledge, as required in Section E.2.1.3.

E.2.2.2 Serious Gaming as method to create Situation Awareness

A further advantage of Serious Gaming beyond the contribution to problems as resilience assessment is provided by the benefit for stakeholders to be confronted with the complex system of interdependent infrastructure systems, their own role and other stakeholders within the system. Since this promotes the perception of the system, the result is a gain of experience among participants (Meijer, 2009) and therefore an increased system awareness (Figure E.3) on behalf of all stakeholders, including the awareness of systemic interdependencies beyond the own direct influence. Thus, apart from an increase in knowledge and experience due to the training, goals and objectives as individual factors can be operationalised (cf. Section E.2.1.4). An important aspect of generating experience through gamification is the exercise of disaster-related strategies without experts bearing the real costs of potentially wrong decisions (Solinska-Nowak et al., 2018).

A learning effect is achieved among the stakeholders since they learn about several systemic aspects simultaneously (Parker et al., 2016; Kourounioti et al., 2018). This includes external factors as well as recognition of the fact that the decision-makers are part of a system. Situation Awareness can be further enhanced by encouraging the stakeholder to reflect his own role, i.e. that the stakeholder understands where her or his own behavior facilitates or impedes solutions for all parties involved. Particularly by requiring stakeholders to interact and communicate with each other, a safe space for discussion and peer-to-peer learning is created and they are enhanced to try to understand systemic interdependencies (Solinska-Nowak et al., 2018; Parker et al., 2016). Thus, Serious Gaming can be seen as a valuable tool to create Situation Awareness, as outlined in Section E.2.1.4.

E.2.3 Applications and design principles of Serious Gaming

E.2.3.1 Applications on transport infrastructure

Serious Gaming is rather scarcely applied in the literature but the number of publications and applications is gaining in importance creating a significant impact on recent research. Nevertheless, the literature on linking Serious Gaming and infrastructures contains few documents (Figure E.4).

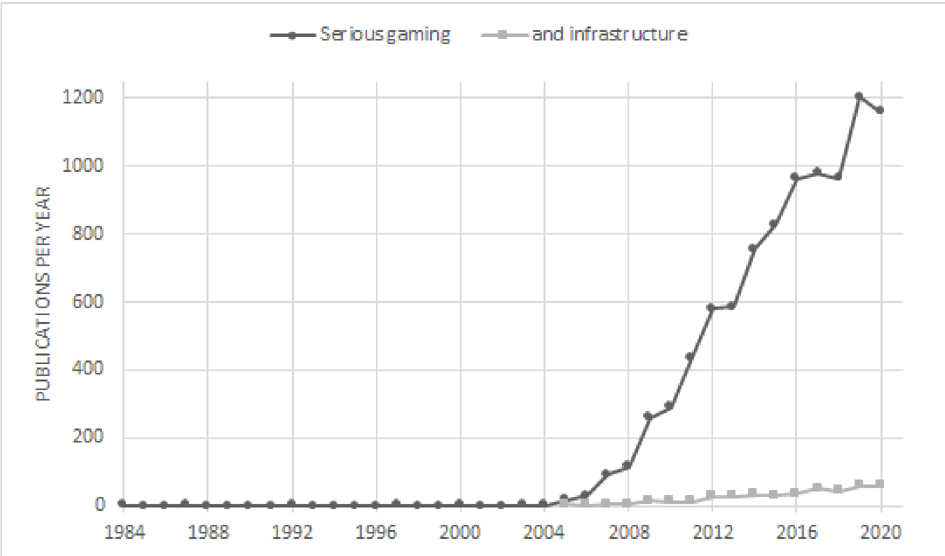

Figure E.4: Publications referring Serious Gaming[2]

In exemplary applications of Serious Gaming in the field of risk management, players are confronted with real-world problems involving risks, such as resource management (Oliveira et al., 2013; Taillandier and Adam, 2018) or climate change adaption and disaster risk reduction, e.g. towards assessing policy preferences (Fleming et al., 2020; Abad et al., 2020). Literature reviews about gamification applications towards disaster risk management reveal that the majority of applications in this field concern the pre-disaster phase for which the aim of raising awareness is explicitly important (cf. Tsai et al., 2020, for a recent example), whereas most applications focus on flood-scenarios (Solinska-Nowak et al., 2018; Kankanamge et al., 2020).

Infrastructure-related applications are scarce (Figure E.4) and mostly solely focus on the purpose of Situation Awareness rather than knowledge gaps in research (Freese et al., 2020; Bekebrede, 2010). Kourounioti et al. (2018) for example conduct serious games with stakeholders in freight transport and aim for a raise of awareness towards synchro modality and observe a learning effect among the players towards the importance of collaboration and coordination towards a resilient

[2] SCOPUS Search (19.05.2021) Search strings:
"Serious gaming": (TITLE-ABS-KEY("serious game" OR "serious gaming"))
"and infrastructure": (TITLE-ABS-KEY("serious game" OR "serious gaming")) AND (infrastructure)
Documents published so far in 2021 (327) were not considered to account for ongoing publications.

transport network. Kurapati et al. (2015) additionally consider training resilience competencies of stakeholders and put forth an elaborated process for game design.

A proposed game to be developed should take into account the identified objectives of both expert knowledge elicitation towards the identification of research gaps and enhancement of Situation Awareness. The effort of the design process should be adequate and can be adjusted by using existing solutions and documented lessons learnt.

E.2.3.2 Game Design principles

The application of Serious Gaming as a valid research instrument is promising since it can address the complexity of socio-technical systems, whereby the method and application of Serious Gaming is elaborated in the following. The design of serious games should follow established procedures (Lukosch et al., 2018). This includes the consideration of the real world interdependent systems (case study), meaning and play, according to Triadic game design which is based on the two design paradigms Concurrent Design and Iterative Design (Harteveld, 2011). Furthermore, the validity of games arises from the four aspects psychological reality, structural validity, process validity and predictive validity (Raser, 1969). Further implications to consider scientific aspects are the inclusion of the problem owner and/or target group in the game design phase. Within the game execution phase, external factors such as motivation, experience, social skills and expectations of players have to be addressed as well as difficulties in the evaluation phase which can arise by the mode of data collection (Lukosch et al., 2018).

Freese et al. (2020) identify accessible principles to be followed in each phase, concerning among others the balance between reality and play and the necessity to reflect upon the level of abstraction and complexity. To address the purpose of gaining research data within the evaluation phase (Section E.2.2.1), qualitative data can be analysed by observer notes, especially to understand players' choices, whereas quantitative data can be extracted by pre- and post-game survey data, among others (Freese et al., 2020; Kourounioti et al., 2018; Kurapati et al., 2017) (cf. Figure E.3). The purpose of Situation Awareness (Section E.2.2.2) can furthermore be addressed by the implementation of a debriefing and discussion session about insights and how the game relates to the real-world system after each session. Parker et al. (2016) show that this raises the learning effect since reflection is a vital part of the learning process (Dewey, 1910).

Figure E.5 shows an exemplary structure of a game session to ensure the reach of both objectives of the present research, as the end of the game session is followed by the analysis of the contribution to the purposes. Figure E.3, which was already introduced, furthermore describes inputs and outputs of a gaming session where roles, rules, objectives and constraints define the game design. In addition to that, load as input refers to the allowing of different configurations of the game while the input factor situation includes the surrounding of a game session which is not included in the game design, mostly referring to the selection and preparation of participants (Meijer, 2009).

The entirety of game mechanisms determines the game category followintg the differentiation between competitive, cooperative and collaborative games. While competitive games focus on

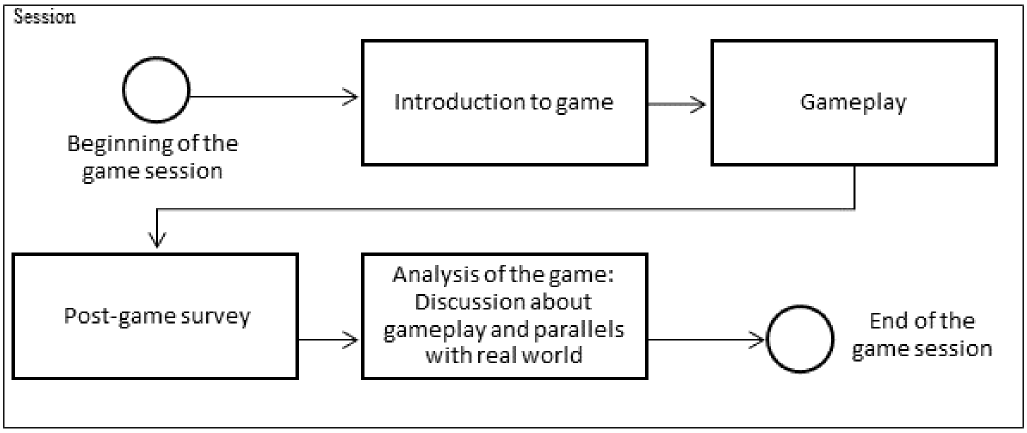

Figure E.5: Possible structure of a game session

conflicting goals of the players, cooperative gaming shows neither completely opposed nor completely coincident goals of the players. Therefore, cooperative players are not guaranteed to benefit equally, or even at all. By contrast, in a collaborative game, all players have the same goal by sharing payouts and outcomes: If the team wins (loses), every individual wins (loses). The players therefore are posed to the challenge to maximize the teams' utility (Zagal et al., 2006).

One advantage of collaborative play is that it increases players' knowledge of the game's associations within the depicted real-world system and thus particularly promotes Situation Awareness. In addition, the players are encouraged to become more involved in the game, as they are motivated to discuss, and have someone to share difficulties instead of blaming themselves for confusion or failure (Squire et al., 2005). Whereas collaborative gaming is used specifically in disaster risk management (Solinska-Nowak et al., 2018), exemplary applications concerning infrastructure rarely make use of collaborative gaming even though they aim to raise awareness about collaboration and communication (Kourounioti et al., 2018).

Challenges have to be overcome in the development of collaborative games, in particular the threat of one player to make all decisions for the team. This can be avoided by providing a sufficient rationale for collaboration by the implementation of different roles and abilities of the players and a sufficiently difficult problem. Another challenge lies in the creation of a satisfactory and probably variable outcome for the players, thus they are motivated and understand the consequences of their actions. Random elements in the game design and mechanisms can furthermore support the games' replayability (Zagal et al., 2006).

Serious games can be implemented both as computer games, which provide an increasing complexity, as well as board games that are fairly constrained in their gameplay (Abt, 1970). Due to their transparency and simplicity, board games are better suited for the analysis of collaborative games. The main difference between the implementation as a board game and as a computer game concerns the communication between the players and probably the instructor (Zagal et al., 2006). Social cohesion is a fundamental element of board games, while the enhanced direct interaction of the players moreover allows an easier transfer back from the game to the real system, considering the evaluation phase of the game (Lukosch et al., 2018). Therefore, the instructor needs to have a high level of game knowledge to mediate and facilitate gameplay towards goal achievement (Young et al., 2012).

On the whole, manifold aspects have to be considered to connect serious gaming and the use case of critical infrastructure maintenance in order to enable a target-oriented application. This includes the specifics of CI maintenance as case study (Section E.2.1), whereby the purposes of expert knowledge and situational awareness (Section E.2.2) can be derived, which must be addressed by the design principles necessary for implementation (Section E.2.3).

E.3 Case: Resilience of German inland waterways

The previous elaborations provided a general framework and structured consideration for the inclusion of stakeholders and expert knowledge in the development of a resilient maintenance strategy supported by the use of Serious Gaming. Subsequently, the application in the context of a specific research project is explained in detail.

E.3.1 Case and initialization

E.3.1.1 Problem understanding

The development of a resilient maintenance strategy is the scope of a research project that pursues the central goal of an improved resilience of the waterway infrastructure in Germany. Project partners of different backgrounds investigate possible effects of the failure of critical waterway infrastructure within a holistic risk management approach. Therefore, the effects and consequences of infrastructure failures are analysed referring to the West German Canal Network as example region, which can then be transferred to further transport infrastructures. The example region is illustrated in Figure E.6 with highlighted locks as construction elements that primarily ensure the function of freight transport. Adjacent industries, in particular an industrial park with chemical companies and well as a coal-fired power-plant, strongly depend on the availability of the waterways.

Figure E.6: Locks across the West German Canal Network

The constructions of German inland waterways are particularly affected by a systemic maintenance backlog and exhibit strong interdependencies to industrial and population systems. The related tasks of problem definition and basic data collection are executed on an interdisciplinary level as depicted e.g. by Wehrle et al. (2020). Since interdisciplinary expert knowledge has a significant influence on the achievement of the project objective, experts and stakeholders, from both science and practice, with their valuable knowledge and judgements are integrated across all project phases making extensive use of participatory elements like workshops and interviews (for Digital and Transport, 2018).

Based on this fundamental understanding of the problem, suitable methods are evaluated following the considerations from Section E.2.1.1 whereby the approach of Hosseini and Barker (2016) was found to be most suitable due to its applicability and because it addresses data availability (cf. Section E.2.1.1).

E.3.1.2 Data collection I

First, data was collected among the interdisciplinary project partners who contribute their expertise in their respective fields as well as specific data and the knowledge about further public and private data sources. The collected data included construction data on infrastructure buildings, including their condition and geolocation, historical data on traffic volumes among transportation modes as well as on closures of waterways, among others.

It quickly became apparent that further expert knowledge was needed to improve the data processing (i.e. by data classification) and to make the best possible use of the diverse data. To ensure the required elicitation of expert knowledge for achieving the goals of the research project, an interdisciplinary workshop concept was developed comprising openly structured working meetings with participants from different disciplines. Within this framework, different questions can be tackled in a cooperative manner using appropriate methods and techniques (Niederberger and Wassermann, 2015). Requirements like a suitable workshop location and a positive working atmosphere were respected, as well as a clear definition of the subject or objective, whereby the composition of the participants also had an important role to play (Beermann et al., 2015; Lipp and Will, 2008).

Expert interviews helped to extract knowledge on the complex systems in scope. The workshop concept served to identify predominantly qualitative interdependencies which could be manifested through open discussions and group work (Section E.2.1). This allowed for the identification of relevant procedures and stakeholders, revealing that the majority of maintenance is carried out as reactive maintenance, which leads to a focus on the short-term coordination of repair measures rather than on long-term investments. The most relevant processes can already be derived from these findings. Figure E.7 depicts a use-case-diagram of dependencies and measures of the identified stakeholders. Thus, the assessment of the socio-technical infrastructure system is translated into a multi-agent problem, which represents the stakeholders and their possible actions and requires further investigation.

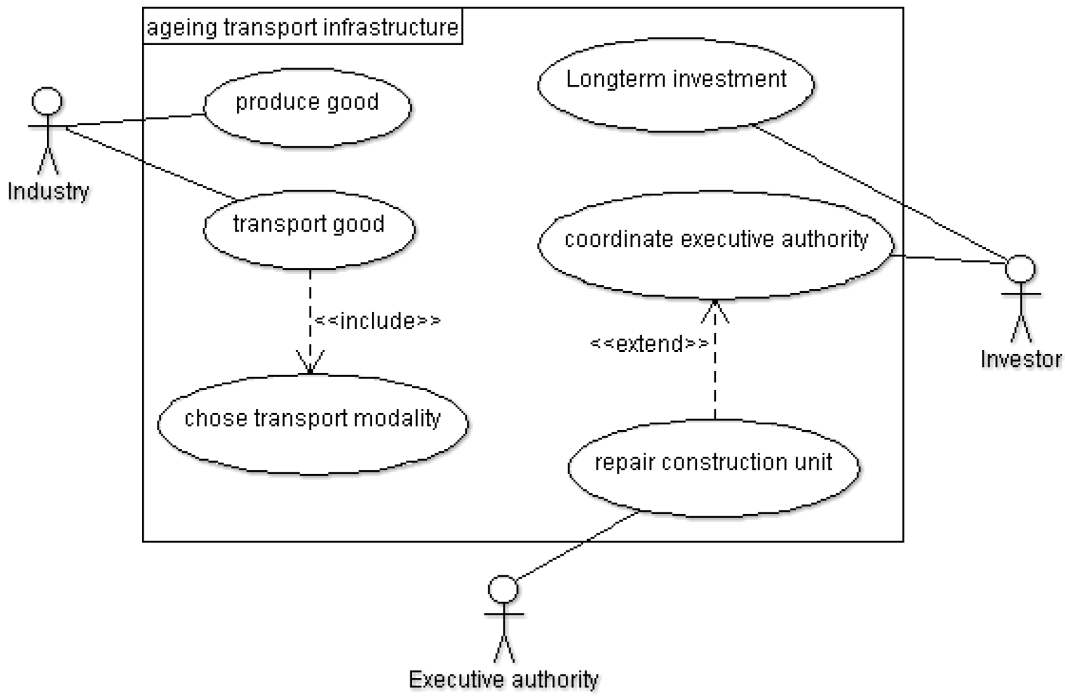

Figure E.7: Use-Case Diagram

E.3.1.3 Resilience assessment based on key-figures

Targeting a Bayesian Network (Hosseini and Barker, 2016), the first step of data collection leads to a reduction of the proposed influencing factors which can be observed and quantified and serve for the application towards the depicted case study defined by the model region and system boundaries. With regard to the system boundaries of the resilience assessment, the transport function of the infrastructure is primarily considered, which in turn depends crucially on the functionality and availability of the numerous locks.

Data collection is based on historical data and expert knowledge as described in the following section. Possible influencing factors are extracted from Hosseini and Barker (2016), adjusted according to the identified specifications of the system in order to account for the expected data availability. Influencing factors of the system's resilience include reliability as part of absorptive capacity and mode flexibility and redundancy as influencing factors for adaptive capacity. Budget restoration and building restoration contribute to the restorative capacity of the building stock.

Since especially the numerous factors which influence absorptive capacity according to Hosseini and Barker (2016) is difficult to assess for our defined system by verified data, this list is reduced to the factor reliability. Figure E.8 and Figure E.9 show exemplarily the calculation for the variable based on historical data about the West German Canal Network of Gast and Wehrle (2019) where data on lock closures was used and cumulated to one distribution. As applied by Hosseini and Barker (2016) we use the truncated normal function derived by the data set and set a critical threshold of 100 days for the variable Time To Failure. This threshold is used to reflect (1) regular closures that do not significantly affect operations and (2) critical thresholds for the industry according to expert interviews. This suggests that the system exhibits an acceptable period of time before a state of unavailability occurs and thus reliability can be considered to be met in 63.47% of the time.

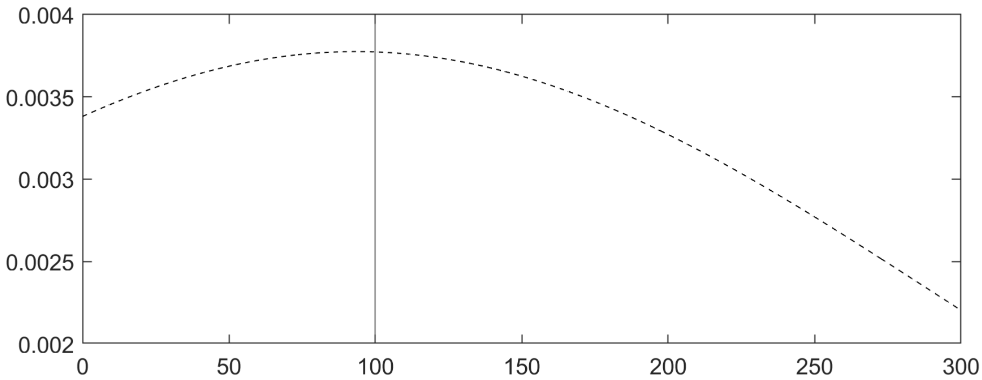

Figure E.8: Truncated Function of Time To Failure[3] (with critical threshold=100 days)

[3] TF~TNORM($\mu = 93.44, \sigma = 199.11, \mathrm{LB} = 0, \mathrm{UB} = 300$).

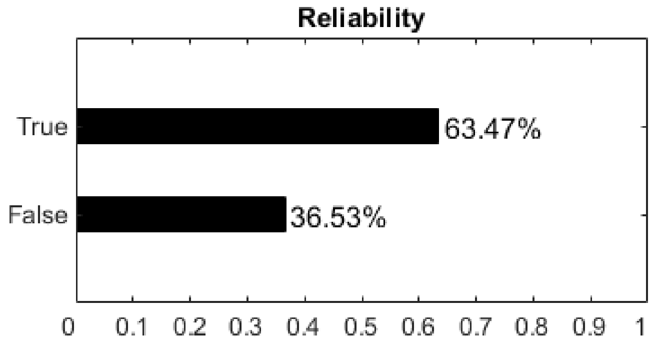

Figure E.9: Calculating the value of "reliability" at the West German Canal Network[4]

Following Hosseini and Barker (2016) variables can be (1) boolean (true/false), (2) qualitative (ordinal) or (3) continuous (known probability distribution). In this first iteration, influencing factors are implemented as Boolean variables of the states True and False, where the True state represents the success state as positive contribution to resilience. The state True of the factor maintenance suggests a successful maintenance while the state False indicates the lack of a successful maintenance. Evaluating all influencing factors on this first level, Table E.1 states the basic characteristics and meanings of the respective variables.

Variable	**True**	**False**
Reliability	Time To Failure is within accepted range of min. 100 Days without failure	Time To Failure is out of the accepted range of min. 100 Days without failure
Mode flexibility	Mode flexibility is available	Mode flexibility is not available
Redundancy	Redundancy can be used to cope with disruptions	Transport network provides no redundancies
Repair: Building restoration	Building restoration can be provided, human-based resources are available	Building restoration cannot be provided because human-based resources are not available
Budget restoration	Budget to restore damaged equipment is available	Budget to restore damaged equipment is not available

Table E.1: Boolean variables of Bayesian Network

In the first iteration, the weights are determined using direct rating (Bottomley et al., 2000) by project participants who have an interdisciplinary background and have developed a shared understanding of the complex observed system (Wehrle et al., 2020), provided by the previous steps of data collection. Figure E.10 shows how the capacity-elements of infrastructure resilience are determined by influencing factors, which represent resilience strategies. These values reflect the contribution of a factor's specification to its superior factor, using the weighted mean function (Hosseini and Barker, 2016).

4 IF(TTF$\geq$100,"True","False"

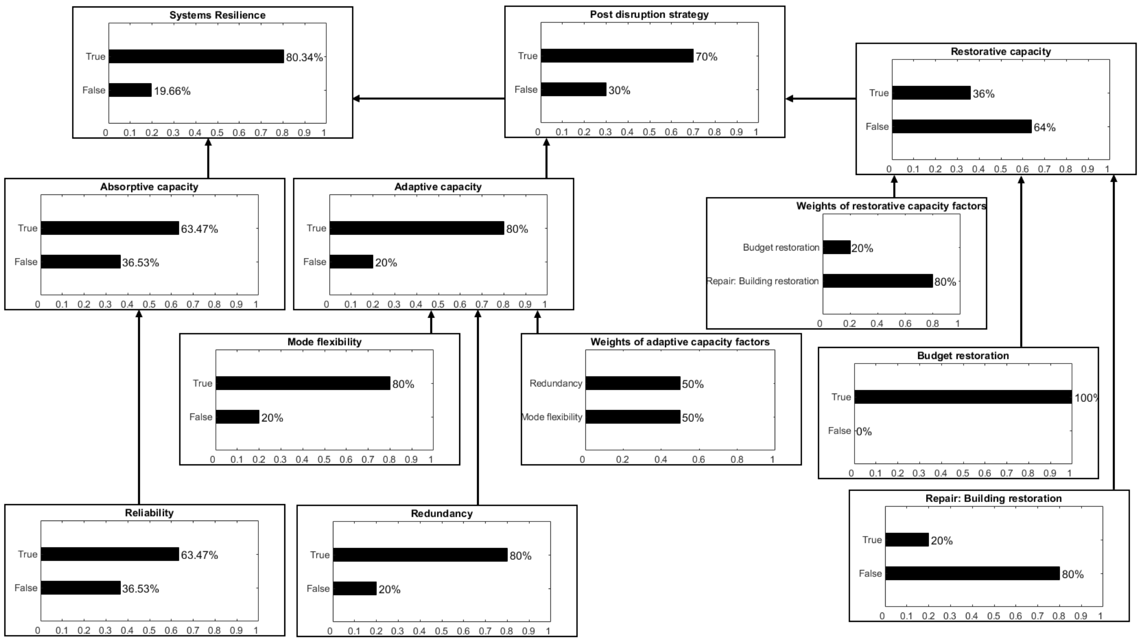

Figure E.10: Bayesian network to assess systems' resilience

The value for mode flexibility (80%) is adopted from Hosseini and Barker (2016), whereas the variable redundancy takes into account redundancies provided by 11 out of 14 locks which have two chambers as well as redundancies among the canal network such as alternative routes (detours). Therefore, the possibilities of usable redundancies is rated by 80%, taking the variable "mode flexibility" as a reference. The assessment of the restorative capacity shows that budget restoration is assumed to be 100% True which means that sufficient budget is available at any time. Among others, this was derived by the first data collection when experts stated that money within the system would be available but is mostly misallocated since e.g. personnel capacities represent a bottleneck, leading towards a weighting of 20% of budget restoration with respect to the restorative capacity. In addition to building restoration, representing barriers for optimal budget allocations as deficits in personnel capacities (Table E.1) , these assumptions lead to an expected restorative capacity of 36%. To address overlapping effects of adaptive and restorative capacities we adapt the NoisyOR function by Hosseini and Barker (2016) as shown in Exp. E.1, representing a boolean operator which is used to assess conditional inter-causal independence (Fenton and Neil, 2018).

$$NoisyOR(Adaptive\ capacity, 0.7, Restorative\ capacity, 0.95, 0.02) \quad \text{(Exp. E.1)}$$

This leads to a probability of 70% that a post-disruption strategy will be successful. In total, we receive a total resilience of the system of 80.34%, as depicted by Figure E.10 and calculated by Exp. E.2.

$$NoisyOR(Absorptive\ capacity, 0.7, Post\ disruption\ strategy, 0.95, 0.02) \quad \text{(Exp. E.2)}$$

E.3.1.4 Reflection

The robustness of this assessment can primarily serve to identify possible contributions of changes in identified resilience factors (e.g. enhance mode flexibility by creating more capacities). Based on this, different possible measures can be compared to improve overall resilience. Furthermore, similar systems can be compared as to prioritize certain regions for maintenance measures.

Nevertheless, the assessment is at high risk for bias but requires comparatively little effort as it uses accessible data and assumptions. Therefore, it can provide a reference point for further calibration, whereas the elicitation of expert knowledge should aim for (1) reviewing whether the number and impact of the influencing factors taken into account are sufficient, (2) reflecting the weights as contribution of influencing factors for resilience and (3) analysing whether the used data quality is sufficient for application.

E.3.2 Application of Serious Gaming

E.3.2.1 Data collection II and enhancing Situation Awareness: Serious Gaming

To address the further need of data collection identified within the reflection, a workshop was conducted built on the knowledge base acquired by the project participants, which was integrated in the application of the Serious Gaming session. Thereby the stakeholders were confronted with a gaming environment, which reflects the researchers' understanding of the considered system. Within the collaborative game, the players are encouraged to reach a common goal through joint interaction. The game is defined by different roles of the players and the time structure together with further assumptions.

Results include first the validation of realistically depicted interactions and second a gain of knowledge for the researchers as well as for the experts involved by increased Situation Awareness. New insights into problems and problem awareness could be recorded and made subject to open discussions to achieve that the stakeholders were directly confronted with the mechanisms and interdependencies of the modeled systems. The developed game is a collaborative serious game as a board game which is based on the commercial game Pandemic (Leacock, 2008). The structure of the game with its implementation details is specified in the following sections.

E.3.2.2 Game Design Phase

Game purpose. As stated before, serious games serve an explicit purpose. This purpose is subdivided into the following subgoals by the purpose system illustrated in the left part of Figure E.11.

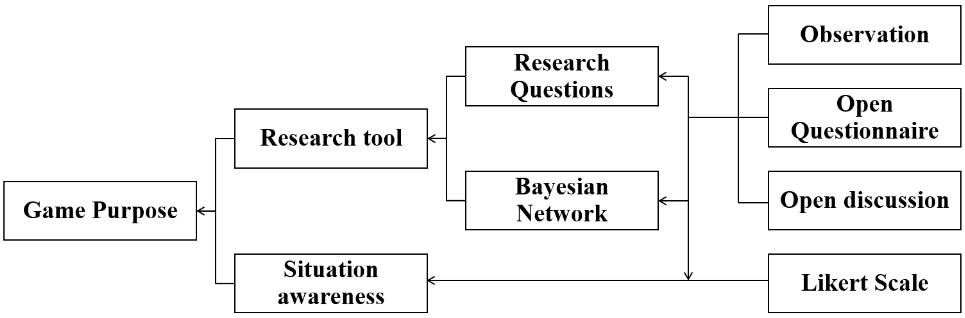

Figure E.11: Purpose system and tools to fulfill

The subgoal research tool relates to the game objective to improve external validity as it confronts experts with realistically depicted interactions and interdependencies, which serves the realistic modelling of the complex system. The explicit objective is the validation of the resilience assessment by updating the initial Bayesian Network, among others, by considering the aims defined in the reflection phase (Section E.3.1.4).

The evaluation of the game furthermore aims to address openly formulated qualitative research questions (RQs) about the complex system. Two of these research questions are exemplarily mentioned here. This research-related subgoal is basically reached by the analysis of results as observations, post-game questionnaires and discussions (Figure E.11).

RQ_1: Which role does communication between investor and executive authority play for infrastructure resilience?

RQ_2: Are delays in maintenance a significant factor that determines infrastructure resilience?

The second subgoal is the gain in knowledge of the experts as a contribution to their Situation Awareness. Situation Awareness can be raised as the stakeholders are otherwise not directly confronted with the mechanisms and interdependencies of the modelled systems. This subgoal is addressed by the game design and through the experts being encouraged to reflect and openly communicate the interdependencies of the complex system. Their insights are documented and evaluated by post-game questionnaires.

Game idea. Players find themselves in a world in which infrastructures are increasingly marked by damage and bottlenecks. Their task is to carry out repair measures and transport goods in a collaborative way that the infrastructure can be maintained and necessary goods can be transported under the threat of exogenous disruptive events and shocks.

Game Design. Previous findings from data collection I (Section E.3.1.2) serve as foundation for the mechanisms of the developed serious game, which is based on the interdependencies of infrastructures as well as their resilience capacities. The importance of the value of communication is acknowledged by the implementation of the serious game as a collaborative board game.

The design of the game takes into consideration the concepts and paradigms, which encounter the discussed possible challenges from Section E.2.3.2. A comprehensible depiction of the infrastructure system is ensured by the mechanisms illustrated in Table E.2.

Aspect of Game	Representation of
Game board	Geographical interdependencies
Game mechanisms	Physical and logical interdependencies
Players and roles	Enhanced representation of physical and logical interdependencies Resilience capacities

Table E.2: Representation of infrastructure system

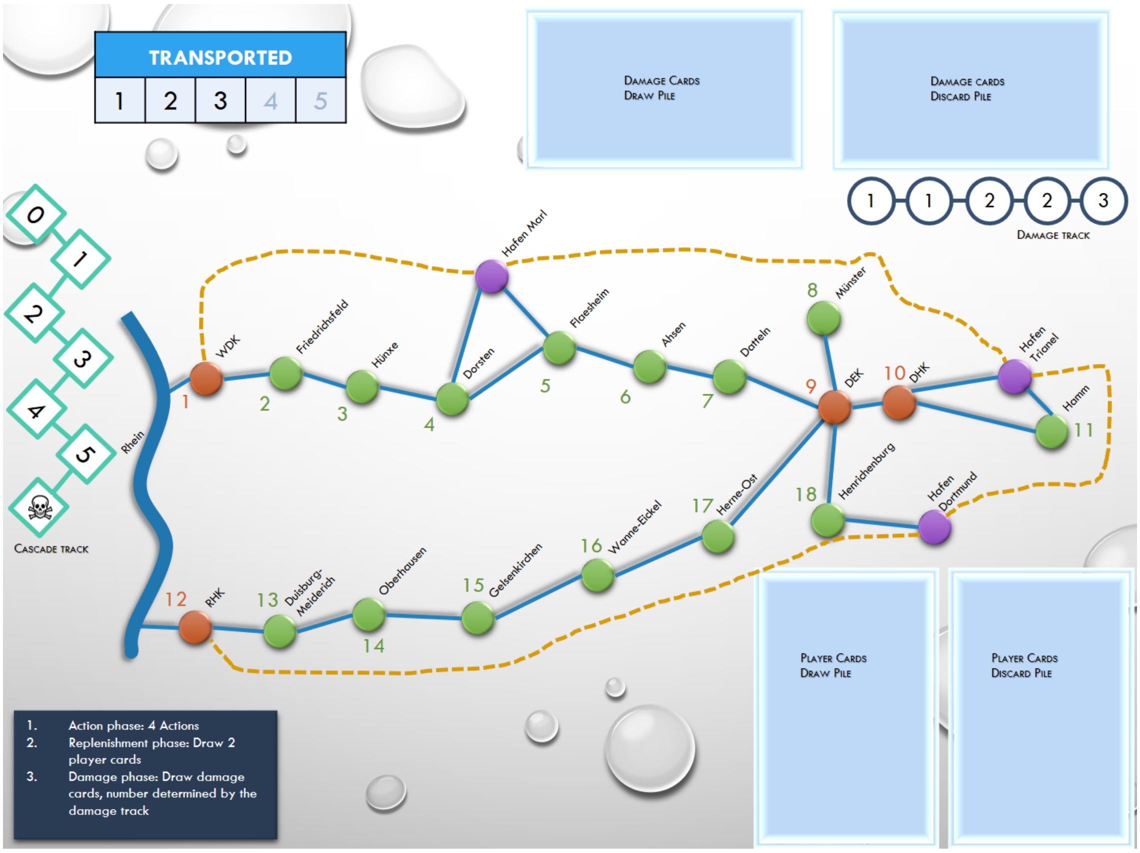

Figure E.12: Game board

The game plan (Figure E.12) consists of a network of transport infrastructures in the area surrounding the West German Canal Network. The nodes represent locks, start and end points of freight traffic such as ports and industrial sites are also tagged like markers to indicate the progress of the game. Furthermore, two piles of cards are used for the depiction of the game mechanisms, which are illustrated on the game board as well as on individual instructions.

Gameplay. All players win by the completion of a certain number of goods transported (blue cubes) and they lose all together, if the infrastructure reaches a specified level of disruption (red cubes). The game mechanisms therefore include the three iterative phases of a players' turn: action phase, supply phase and damage phase. The action phase consists of up to four possible moves of the active player corresponding to their abilities.

The last two phases are determined by random effects: The damage phase randomly chooses locks that are damaged by drawing corresponding cards. It is taken into account that already damaged infrastructure elements reappear more often in the damage phase than the cards of the not yet damaged locks. Damages are symbolized by red cubes, which are placed on the infrastructure elements which have a cascade damage threshold. This means that if there are as much cubes as the cascade damage threshold, further damages are spread to connected infrastructure elements as to symbolize congestion effects and an acceleration of damage in the network. The system can only handle a certain threshold of cascades (maximum cascade level) before it collapses and the players lose.

The supply phase serves the budget restoration by providing capital cards. Still, simultaneously, the drawing of these cards can cause disruptive shocks, which lead to the sudden destruction of a lock. Those random elements address the replayability and at the same time simulate the unpredictability of possible disruptions while the continuous deterioration accounts for the observed ageing effects.

The implementation of different roles with different abilities as well as the degree of complexity ensures the need for collaboration. The players' activities reflect the resilience capacities. For example, the action of maintenance corresponds to an increase in absorptive capacity since the state of the canal network corresponds to locks that are available for repair and others that are damaged and therefore must be repaired.

The players should consult each other and openly make suggestions. Nevertheless, it is ultimately the player whose turn it is to make the decision. Each player can move along the infrastructure network. Table E.3 shows the three game characters that can perform individual actions and have the corresponding starting equipment. The abilities are derived from the use-case diagram in Figure E.7, which represents the basic assumptions about real-world interactions within the infrastructure system.

	Industry	**Investor**	**Executive authority**
Abilities	Produce goods Transport goods Shift transport modality	Long-term repair Coordinate controller Transfer MU towards executive authority	Repair Transfer MU
Starting Equipment	2 MU 2 goods at production site	2 MU	2 MU

MU = monetary unit

Table E.3: Roles of the players with their abilities and starting equipment

Overall, the character of the complex system is addressed by the Game Design Phase as the players have to adapt to their respective actions and reactions within the game (adaptability) which is resulting in strategies as self-organized reactions. The game also represents stable components of the transport system as the network characteristic is given and slow to change. The cumulative dimension is reflected by changes in minor components having potentially large effects on other components in the gameplay as perceived in the real-world system, whereas several possible actions and events as mode shifts or major destructions address phase transitions that mark complex systems as such.

E.3.2.3 Calibration

The identified game design principles demand the provision of a realistic, but not inflated, chance of winning and simultaneously entail an adequate representation of aspects of the real-world system, which requires thorough calibration. This is achieved by implementing the game mechanisms in Python with several variables such as different quantities of cards, levels of disruption as constraint to fail, among others. The implementation of simple minded agents, meaning agents with static objective functions and simple heuristics to select their limited set of possible actions, provides thresholds to address when varying the game to adapt to further knowledge or objectives.

Figure E.13 illustrates exemplarily the impact of the cascade damage threshold on the win rate and the average number of turns. The simulation shows that an implementation of a cascade damage threshold of 3 creates the best outcome as to serve for the aforementioned game design principles. Notably, this implementation satisfies the requirement for a sufficient probability of winning, since players are on average just as frequently likely to experience a sense of accomplishment as a sense of defeat.

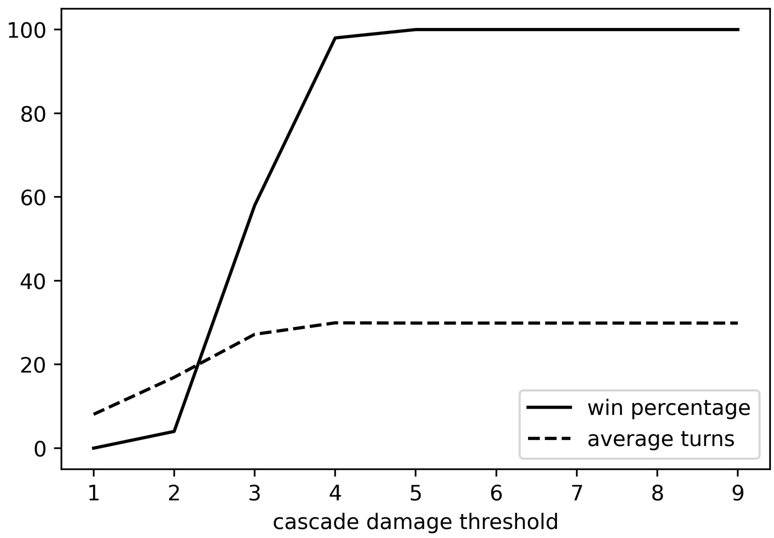

Figure E.13: Impact of the cascade damage threshold on the gameplay

In addition to the calibration of the generally valid game mechanisms, the transporting target, which depends on the start, destination and transport amount, must also be well calibrated. Figure E.14 shows that the rate declines in an approximately linear way if more freight units must be transported to the target node. Increasing the cascade damage threshold can mitigate this effect.

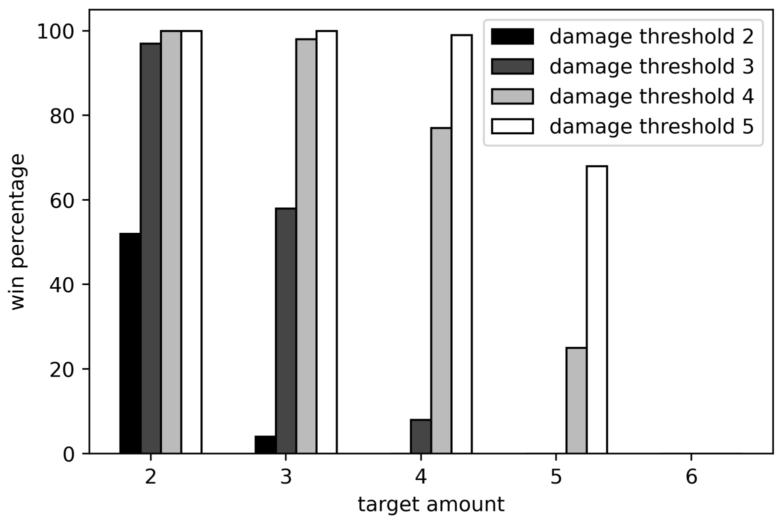

Figure E.14: Dependency of win percentage on target amount

Since we chose a cascade damage threshold of 3 cascades, we chose to use a target amount of 4 transport units. Further calibrations are executed and subject to a combined analysis, the description of which would exceed the scope of this elaboration.

E.3.2.4 Execution and Evaluation Phase

The game was implemented within the scope of the before mentioned research project. Therefore it is necessary to involve stakeholders of transport infrastructure as game participants to achieve the research purposes (Section E.2.2). Although the game can also serve as an entertainment game in itself, the players are to be observed with regard to their respective expertise. Accordingly, the game is primarily aimed at the relevant stakeholders and experts (Section E.2.1.3), whereby further requirements for game participation are not necessary, and non-experts with their lay knowledge can also contribute to ideas of valid implementation. As the circle of experts predominantly consists of specialists of logistics and infrastructure maintenance as well as scientists, this group is also confronted with complex contexts in its everyday work. Hence, for this type of stakeholder group it is rather easy to understand and proactively shape the contexts simulated by the game which is a big advantage for solving such a rather intricate task.

A preplay session was executed with non-experts who are not familiar with the subject [NE] purely for the purpose of calibration and to check for comprehensibility. The second game session included two parallel gameplays by experts from science [SC], industry [IND] and public authorities as investor [INV] and executive authorities [EA], as shown in Table E.4 and had a duration of about

Role in game	S1	S2-1	S2-2
Investor	NE	INV	IND
Executive authority I	NE	SC	EA
Executive authority II	NE	EA	EA
Industry	NE	IND	SC

Table E.4: Participants of game sessions

one hour for the introduction and gameplay. Another hour was used for the post-game survey and an intensive debriefing session (Figure E.5).

In order to reach and evaluate the beforehand identified game targets, the gameplay was observed by the project participants. Furthermore, the players answered a questionnaire directly afterwards and discussed the gameplay within their game session whereas the discussion after the parallel session (S2) included both groups of players. The discussion was structured considering the aims of the reflection phase (Section E.3.1.4) and the research questions (Section E.3.2.2) as the researchers observed the discussion and took notes to make sure that all aspects have been addressed.

The questionnaire after the game session asked about the player's role, the reason for the end of the game, and the following open questions about restrictions with respect to resilient freight transport as a game goal:

(1) Which restrictions could you identify in the game?
(2) What restriction did you feel was the biggest obstacle?
(3) Does this restriction exist in the real-world system?
(4) Do other restrictions exist in the real-world system that can be classified in the depicted contexts, but are not taken into account by the game?

Moreover, the experts were asked to give a score for the following statements on a 4-point Likert (1932) scale from "Agree" to "Disagree":

(5) I enjoyed playing the game
(6) I was challenged to reflect on facts of the real-world system
(7) I was able to put myself in my role well
(8) The players collaborated well

Hence the evaluation phase could address the game purpose as stated in Figure E.11. While the Likert Scale aims for the evaluation of the degree of Situation Awareness reached, the other instruments mainly contribute to the serious game as research tool by addressing research questions about the system and its resilience as well as quantitative data to use within the Bayesian network as to update (1) data sources by targeted data processing, (2) weights by observed interdependencies and therefore (3) the overall quantity and expression of variables.

E.4 Results

In this section we provide an overview of the most important findings. In a first step, we analyse benefits of the game as a research tool, pertaining to research questions and the Bayesian network. Afterward, we examine the contribution of the implemented game toward Situation Awareness.

E.4.1 About the research tool as Game purpose

E.4.1.1 Research questions

The research questions (Section E.3.2.2) could be tackled as depicted in Figure E.11. Observer notes were used to answer RQ_1*: Which role does communication between investor and executive authority play for infrastructure resilience?*

The observations therefore reveal a high need for communication between investor and executive authority within the game. Furthermore, it was observed that the players drew comparisons of the in-game communication with the stakeholder communication in the real-world system and thereby critically reviewed the latter. The debriefing session moreover revealed the necessity of communication as game element which reflects the real-world setting properly. This can be found, among others, in the list of in-game aspects that the consensus of the experts identified as realistically mapped with regard to the real-world system (list order depicts discussion succession):

(1) Industry has a lot of money, can thus change the mode of transport, but is not able to support the Executive Authority
(2) Industry wants to stay in dialogue with executive authority
(3) Communication between investor and controller is necessary
(4) Movement in game represents the timing bias in real-world decisions
(5) Timeliness of decisions: Transportation short term, investment long term
(6) Stakeholder Ratio 3:1 of administration to shippers
(7) Dramatic of repair and yet decay
(8) Rail takes goods from ship, not from the road. Therefore, this should become more expensive.

Hence, the answer to RQ_1 can be summarized as follows: Communication between investor and executive authority play an elementary role for infrastructure resilience since measures cannot be coordinated otherwise and the need for in-time-measures is high due to the deteriorating network condition – both in the game and in the real-world system (Table E.5).

RQ_2*: Are delays in maintenance a significant factor that determines infrastructure resilience?* is addressed within the list of realistic mapped aspects, as point (4) above states that there is a timing bias within maintenance decisions. The answers to the post-game survey in Table E.5 show furthermore that the external control as decision tool of the investor towards executive authorities can be seen as a big restriction, which also exists in the real-world system.

Role [Real]	Role [Game]	Biggest restriction	Existing	Not depicted
Industry	Investor	Industry cannot financially support the maintenance	Yes	-
Investor	Investor	Deteriorating condition of locks	Yes	Damage to alternative transport infrastructure; Staff deficit in maintenance
Science	Industry	External control of investor towards executive authorities	Yes	Time needed for repair depending on extent of damage
Industry	Industry	Transfer of resources towards maintenance	partial	Suggestion: adding destination Rotterdam
Science	Executive Authority	Distances, investment resources, deteriorating condition of locks	partial	Damage to alternative transport infrastructure
Executive Authority	Executive Authority	Staff deficit in maintenance	Yes	Other functionalities besides transport function (water management, tourism, ecology)
		Industry cannot financially support the maintenance	Yes	Further political/societal restrictions like blanket personnel reduction
Executive Authority	Executive Authority	Sudden formation of severe damages	Yes	
Executive Authority	Executive Authority	Repeated damage of the same assets	Yes	

Table E.5: Results of post-game survey

Besides the explicit mentioned research questions, further findings included the validation of realistically depicted interdependencies as induced assumptions such as implications for intermodal transports (no. 8) or repeated damages of the same assets due to vulnerable construction (Table E.5).

Inadequate assumptions of the model were discussed by the experts, which is important for the correct interpretations of the current processes. Aspects, which were insufficiently represented in the eyes of the stakeholders, are extracted from the discussion and summarized in Table E.6.

As previously mentioned, these foremost qualitative findings serve to identify relations between components within the complex system of infrastructure and its resilience as to provide helpful insights towards its modeling.

E.4.1.2 Bayesian network

An update of the Bayesian network is described in the following section. Note that the following findings are intended to provide primarily an attempt to the more effective inclusion of data and an incentive for a more in-depth quantitative, data-driven analysis. The highlighted factors are backed up with quantitative tendencies, which were derived from the qualitatively evaluated results.

Repeated damages of the same assets imply the necessity to take the initial condition of a construction into consideration. This data is available for constructions as Condition Grades (CG) of the interval [1 – no damage; 4 – severe damage] within the database WSVPruf (Görler et al., 2007).

	Reflection
Waterways Network	• Small locks were maintained in the recent past
	• Spread of damage in the network is less realistic
Executive Authority	• Implement capital directly without consideration that staff capacity may not be available (realization possible through dice).
	• Current personnel savings
Investor	• Competition with other investments
Industry	• Competition between different industry participants
	• Push barge must be coupled first → lock lengths vary, so redundancies cannot be effectively exploited
	• Short-term shifting often not possible
	• Alternative modes of transport do not fail in the game
Further	• Neglect of other areas; other destinations, e.g.: destination Rotterdam, or further tasks of authorities that these have to neglect due to the higher workload
	• In the real-world system, a higher risk results from the fact that transports are short-term and repairs are long-term

Table E.6: Discussion excerpt over insufficiently represented aspects

Considering the locks in the research yields the following insight: Just 2 out of 12 locks have a better building stock condition grade than the worst grade (4). We transferred these results to a Boolean variable by the following Boolean expression:

$$(IF\ CG < 4, \text{“}True\text{”}, \text{“}False\text{”}) \quad \text{(Exp. E.3)}$$

This distribution is weakly correlated with the Mean Time Between Failures (MTBF), but the building stock condition data is less biased than the empirical data of failures. In addition, warning times before disruptions were observed to be a major factor affecting industry performance, more significant than MTBF. Therefore, CG and furthermore the warning time is taken into consideration towards determining the factor “maintenance” instead of the sole consideration of MTBF. The warning time can be derived following the approach from Gast et al. (2020). The authors provide an analysis of warning times and identification of critical threshold of a minimum of two weeks which are needed by the industry to prepare for measures towards disruptions in waterways. An optimized warning time of 21 days is taken into consideration by a truncated normal function that accounts for the above data with a lower bound (LB) of zero days and an upper bound (UB) of a maximum of 200 days warning time.

$$TF \sim TNORM(\mu = 20.82, \sigma = 39.02, LB = 0, UB = 200) \quad \text{(Exp. E.4)}$$

In addition, the Boolean expression

$$(IF\ WT > 21\ days, \text{“}True\text{”}, \text{“}False\text{”}) \quad \text{(Exp. E.5)}$$

reflects the extracted experts' knowledge. The aggregation of the factors is implemented by direct weighting considering warning time for disruptions that play a decisive role for the reliability of the waterways system. Thus, warning time is given a weight of 80% with respect to reliability and the condition grade is implemented with a weight of 20% since most of the infrastructure is assigned the worst condition grade, but still relatively high levels of reliability are achieved (Gast and Wehrle, 2019).

Table E.7 shows the characteristics and meanings of the respective variables, which are described below:

	True	**False**
Reliability		
Warning Time	≥ 21 days	< 21 days
Condition	Condition grade < 4	Condition grade $= 4$
Maintenance		
Personnel capacities	Construction measures can be provided, human-based resources are available	Construction measures cannot be provided because human-based resources are not available
Budget allocation	Budget for construction measures is available	Budget for construction measures is not available
Mode flexibility		
Resilience of other infrastructure	Resilience of alternative transport modes offers a sufficiently high level	Resilience of alternative transport modes offers no sufficiently high level
Competing industries	Competing industries shift less amounts of freight towards other modes than remaining capacities	Competing industries shift more or equal amounts of freight towards other modes than remaining capacities
Effective Redundancies	Redundancy can be used to cope with disruptions	Transport network provides no effectively usable redundancies

Table E.7: Boolean variables of Updated Bayesian Network

In the discussion, the direct conversion of capital by the executive authority was criticized since it ignores the fact that personnel capacity may not be available and thus influences the repair activities, especially under current staff saving restrictions (Table E.5; Table E.6). Moreover, the representation of the investor player neglects the competition of the displayed investment opportunities with other investments, which reduces the potential of budget restoration (Table E.6). This leads to a limitation of the budget variable "Budget allocation" which takes into account whether money can be accessed for specific measures. This value is still assessed by 80% because there is sufficient budget allocated towards waterways according to the retrieved expert knowledge.

Whereas the first iteration of the Bayesian network already stated alow availability of human resources, the results of this study reveal that personnel capacities are the drastic bottleneck of infrastructure resilience. Therefore, the probability of availability of sufficient human-based resources taking into account the high number of arising necessary construction measures is lowered to 10%.

Since both budget and personnel address absorptive capacity (maintenance) as well as restorative capacity (restore damaged construction) these variables have to be taken into account for both capacities. It is assumed that for regular maintenance still budget allocation is the driving factor whereas unexpected damages confront the staff shortage in the first place as most of the human resources are busy with maintenance activities.

Further findings include that mode flexibility is not only dependent on a company's preferred choice but also on the resilience of other infrastructure since it has to be taken into account that street and railways can suffer from disruptions, too (Table E.6). However, the extension to other infrastructures provides complementary effects on validity since it offers not only the chance to realize an improved resilience assessment of these infrastructures but it could also increase the validity of our approach due to the indicated interdependencies. Moreover, the mode flexibility is highly dependent on the choices of competing industries since transport capacities are limited. Therefore, the resilience of the remaining infrastructures can only be used to a certain extent, resulting in the depicted weighting of the factors determining mode flexibility.

The results in Table E.6 show furthermore a significant overestimated influence of redundancies within the network which are, in fact, much more limited in usability. This is sufficient justification to reduce the assessment of effective redundancies in quite a drastic way. Simultaneously, the results lead us to replace the overall weighting for adaptive capacity by using Exp. E.6.

$$NoisyOR(Effective\ Redundancies, 0.7, Mode\ flexibility, 0.95, 0.02) \qquad \text{(Exp. E.6)}$$

According to Exp. E.6, a high level of adaptive capacity can be achieved if either effective redundancy or mode flexibility can be provided on a high level.

Furthermore, we adapt again the NoisyOR function by Hosseini and Barker (2016) according to Exp. E.7.

$$NoisyOR(Adaptive\ capacity, 0.7, Restorative\ capacity, 0.95, 0.02) \qquad \text{(Exp. E.7)}$$

We obtain a probability of 50.11% that a post-disruption strategy will be successful. These findings result in an elaborated version of the beforehand conducted Bayesian network as depicted in Figure E.15. The overall system resilience is assessed at a level of 71.35%.

E.4.1.3 Outlook Bayesian network

The findings lead to a 9.01% reduced systems resilience and to a larger Bayesian network which implies the significance of neglected as well as over- and underestimated influencing factors. As stated before, it must be noted that the depicted values are mostly derived from qualitative expert knowledge and need more data-driven assessments within the scope of further research. Mostly the

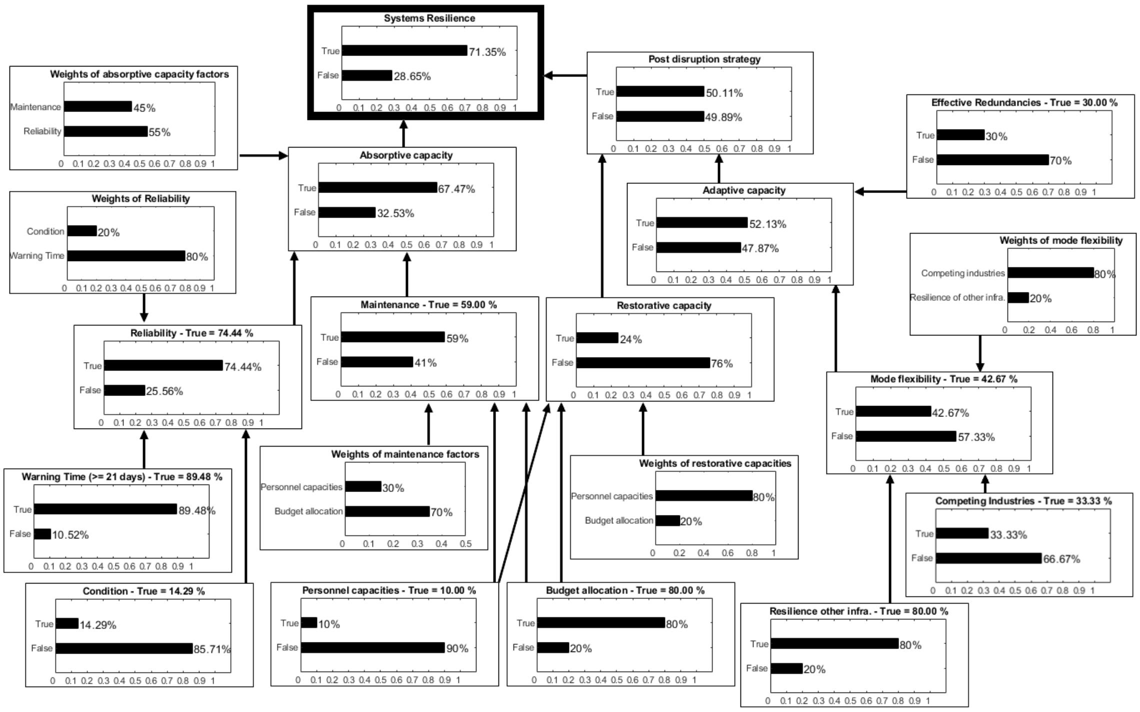

Figure E.15: Updated Bayesian network

variables of adaptive and restorative capacity need more data-driven assessments. This confirmes the need for a further feedback loop as depicted within the research framework.

Furthermore, the resulting resilience values of the networks developed within the iterative research process are not meaningful to be compared among themselves. Instead one should compare their sensitivity with respect to changes in specific parameters which demonstrate possible measures to enhance resilience. The updated network therefore allows for more precise strategies since the adjustment levers are more obvious than before.

E.4.2 About Situation Awareness as game purpose

The game purpose of enhancing Situation Awareness among stakeholders is evaluated by the post-game questionnaire based on Likert-Scaled questions (Section E.3.2.4) which are analysed in Figure E.16 by referring to the questions (5)-(8) by the boxplots. It can be stated that all players felt to be challenged to reflect on the real-world system and that they were able to put themselves in their roles well. Since reflection and experience significantly contribute to Situation Awareness (Figure E.2) the game is evaluated to be a contribution to enhance Situation Awareness among the complex systems of transport infrastructure maintenance and freight transport. The observer notes and notes of the debriefing session furthermore show that the stakeholders displayed learning effects about observed interdependencies and among the finding of a consensus.

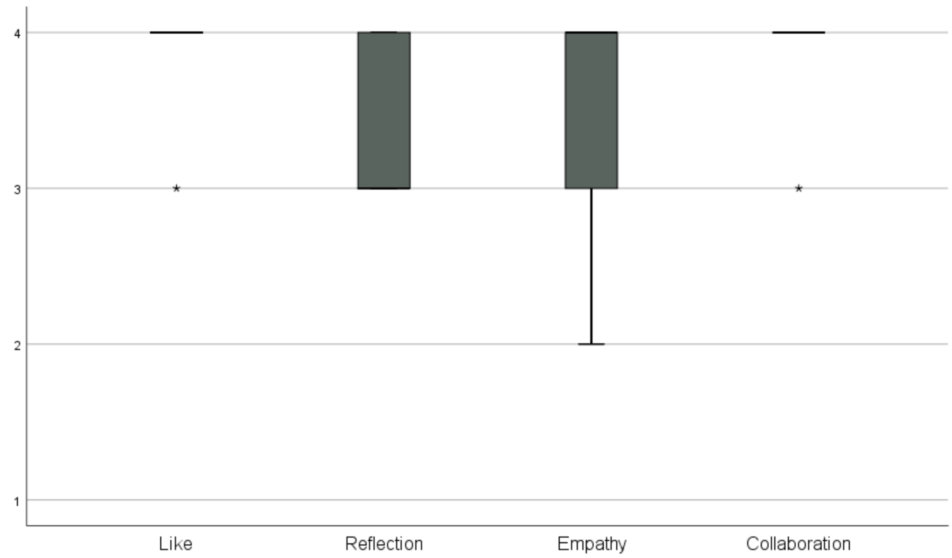

Figure E.16: Evaluation of Post-game questionnaire

The fact that all the players enjoyed the game and found the collaboration to be constructive enhances the application of Serious Gaming as stakeholders must be willing to share their knowledge and therefore be positively disposed towards a constructive exchange and knowledge elicitation.

E.5 Discussion and Conclusion

E.5.1 Potential of Serious Gaming

The findings of the conducted research have provided significant contributions to the understanding of mechanisms, which are essential for the assessment of the resilience of transport infrastructures. Furthermore, an enhanced Situation Awareness among stakeholders could be identified. These first testing game sessions revealed a high potential to use Serious Gaming for both purposes as well as to optimize the evaluation phase towards obtaining more reliable data.

The presented game and underlying research concept shows an approach to identify influencing factors among complex real-world systems as the authors demonstrate the potential of Serious Gaming for the elicitation of expert knowledge in interdisciplinary research projects. Especially the processing of multi-agent problems in complex socio-technical systems can benefit from a game based acquisition of expertise. Collaborative board games show to be powerful tools by highlighting the importance of communication in order to analyse the perception of the players as in the conducted research the stakeholders of infrastructure maintenance.

Concepts and methods for designing Serious Games from the literature support an efficient design phase and can ensure a gainful implementation. In the evaluation phase, particular attention must be paid to the possible evaluation in the form of combining the results of the use case with other research methods such as Bayesian networks.

The foremost contribution of Serious Gaming as a research tool results from the fact that when the stakeholders meet in a different environment, where they all have to represent their interests in tough debates, fewer of the insights found here are visible. By putting them in a different environment and position than the one they are used to, the stakeholders are also inspired to reflect the complex system, their position and their actions which has a real potential to strengthen the resilience of the infrastructure system of which they are part.

In addition to the research results, learning successes can be achieved amongst responsible persons, which is creating a Situation Awareness. This includes knowledge about mechanisms of other institutions, perception of the own institution as well as the understanding of further consequences of own actions. The possible expansion of the application area within the framework of training concepts is shown hereby. As part of a training concept, continuous improvement and repetitions of playing sessions can lead to enhance and keep up Situation Awareness and communication between the stakeholders across their institutions.

For the general application of Serious Gaming, it can be said that the development effort can be significantly reduced by taking an orientation on existing games, even outside the field of research. Nevertheless, further work has to be conducted to serve for better evaluation and an improved use of the results towards the research objective. Research questions must be well-designed and evaluation processes have the need to be calibrated in close coordination with resilience assessment methods.

The software-based calibration furthermore enables the implementation of different strategies using heuristics or machine learning which can provide powerful insights towards strategies of the stakeholders in the real-world system.

E.5.2 Limitations of Serious Gaming

One of the biggest obstacles of the application of Serious Gaming might be the effort for development and calibration, which can be reduced by the orientation on existing games as well as on a software-based calibration to reduce the effort of multiple gaming sessions to be played with real-world players.

While collaborative Serious Gaming is shown to be a powerful tool to raise Situation Awareness and to create a dialogue of stakeholders, the transfer of the results to the Bayesian network can be identified as most critical within the scope of the presented research and therefore must be subjected to strict validation. As suggested, the presented work regarding the contribution towards resilience assessment shows an intermediate state of work, whereas the final resilience assessment tool as Bayesian network is to be finished separately. Nevertheless, the results can serve to identify possible data sources and application biases to be regarded for.

Further applications of the developed game could include the repeated application with different groups of players and participant groups, which could contribute to the identification of potential bias factors. Comparison groups of completely unconnected people could be considered as well as homogenous player groups of one of the stakeholders.

Acknowledgements

The authors want to thank the partners in the joint research project for Digital and Transport (2018). The project is funded by the security research program (www.sifo.de) of the German Federal Ministry of Education and Research (BMBF; grant number 13N14697). Special thanks go to the participants of the survey, who shared their expertise, thereby supporting this research.

References

Abad, J., Booth, L., Baills, A., Fleming, K., Leone, M., Schueller, L., Petrovic, B. (2020). Assessing Policy Preferences amongst Climate Change Adaptation and Disaster Risk Reduction Stakeholders using Serious Gaming. *International Journal of Disaster Risk Reduction*, *51*, 101782.

Abt, C. C. (1970). *Serious Games*. Lanham, MD: University Press of America.

Alcaraz, C., Zeadally, S. (2015). Critical Infrastructure Protection: Requirements and Challenges for the 21st Century. *International Journal of Critical Infrastructure Protection*, *8*, 53–66.

Alvarez, J., Djaouti, D. (2011). An Introduction to Serious Game Definitions and Concepts. *Serious Games & Simulation for Risks Management*, *11*(1), 11–15.

Argyroudis, S. A., Mitoulis, S. t., Winter, M. G., Kaynia, A. M. (2019). Fragility of Transport Assets exposed to Multiple Hazards: State-of-the-Art Review toward Infrastructural Resilience. *Reliability Engineering & System Safety*, *191*, 106567.

Ayyub, B. M. (2014). Systems Resilience for Multihazard Environments: Definition, Metrics, and Valuation for Decision Making. *Risk Analysis: An official Publication of the Society for Risk Analysis*, *34*(2), 340–355.

Beermann, S., Augart, E., Schubach, M. (2015). *Workshops: Vorbereiten, Durchführen, Nachbereiten*. Freiburg: Haufe-Lexware GmbH & Co. KG.

Bekebrede, G. (2010). *Experiencing Complexity: A Gaming Approach for Understanding Infrastructure Systems* (Dissertation). TU Delft, Delft.

Bocchini, P., Frangopol, D. M., Ummenhofer, T., Zinke, T. (2014). Resilience and Sustainability of Civil Infrastructure: Toward a Unified Approach. *Journal of Infrastructure Systems*, *20*(2), 04014004.

Bottomley, P. A., Doyle, J. R., Green, R. H. (2000). Testing the Reliability of Weight Elicitation Methods: Direct Rating versus Point Allocation. *Journal of Marketing Research*, *37*(4), 508–513.

Box, G. E., Tiao, G. C. (1992). *Bayesian Inference in Statistical Analysis*. Hoboken, NJ, USA: John Wiley & Sons, Inc.

Cooke, N. J. (1994). Varieties of Knowledge Elicitation Techniques. *International Journal of Human-Computer Studies*, *41*(6), 801–849.

Cooke, R. M., Goossens, L. H. J. (2004). Expert Judgement Elicitation for Risk Assessments of Critical Infrastructures. *Journal of Risk Research*, *7*(6), 643–656.

Craighead, C. W., Blackhurst, J., Rungtusanatham, M. J., Handfield, R. B. (2007). The Severity of Supply Chain Disruptions: Design Characteristics and Mitigation Capabilities. *Decision Sciences*, *38*(1), 131–156.

Crookall, D. (2010). Serious Games, Debriefing, and Simulation/Gaming as a Discipline. *Simulation & Gaming*, *41*(6), 898–920.

Department of Homeland Security (Ed.). (2016). *Critical Infrastructure Threat Information Sharing Framework: A Reference Guide for the Critical Infrastructure Community.*

Dewey, J. (1910). *How We Think.* Boston: D.C. Heath and Company.

Endsley, M. R. (1995). Toward a Theory of Situation Awareness in Dynamic Systems. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *37*(1), 32–64.

Eusgeld, I., Nan, C., Dietz, S. (2011). "System-of-Systems" Approach for Interdependent Critical Infrastructures. *Reliability Engineering & System Safety*, *96*(6), 679–686.

Federal Ministry for Digital and Transport (Ed.). (2019). Masterplan Binnenschifffahrt.

Federal Ministry of the Interior and Community (Ed.). (2009). Nationale Strategie zum Schutz kritischer Infrastrukturen: KRITIS-Strategie.

Fenton, N., Neil, M. (2018). *Risk Assessment and Decision Analysis with Bayesian Networks* (2nd ed.). Milton: Chapman and Hall/CRC.

Fleming, K., Abad, J., Booth, L., Schueller, L., Baills, A., Scolobig, A., . . . Leone, M. F. (2020). The Use of Serious Games in Engaging Stakeholders for Disaster Risk Reduction, Management and Climate Change Adaption Information Elicitation. *International Journal of Disaster Risk Reduction*, *49*, 101669.

for Digital, F. M., Transport. (2018). *Verbundforschungsvorhaben Resilienz kritischer Verkehrsinfrastrukturen am Beispiel der Wasserstraßen.* Retrieved from `https://www.sifo.de/sifo/de/projekte/schutz-kritischer-infrastrukturen/verkehrsinfrastrukturen/preview-resilienz-kritischer-v-am-beispiel-der-wasserstrassen/preview-resilienz-kritischer-v-am-beispiel-der-wasserstrassen.html`

Francis, R., Bekera, B. (2014). A Metric and Frameworks for Resilience Analysis of Engineered and Infrastructure Systems. *Reliability Engineering & System Safety*, *121*, 90–103.

Freese, M., Lukosch, H., Wegener, J., König, A. (2020). Serious Games as Research Instruments – Do's and Don'ts from a Cross-Case-Analysis in Transportation. *European Journal of Transport and Infrastructure Research*, *20*(4), 103–126.

Gast, J., Wehrle, R. (2019). Application of the Concept of Supply Chain Reliability for an Availability Assessment of Inland Waterway Systems.

Gast, J., Wehrle, R., Wiens, M., Schultmann, F. (2020). Impact of Notification Time on Risk Mitigation in Inland Waterway Transport. *Hamburg International Conference of Logistics (HICL)*(2020).

Gay, L. F., Sinha, S. K. (2012). Novel Resilience Assessment Methodology for Water Distribution Systems. In R. J. Card M. K. Kenny (Eds.), *Pipelines 2012* (pp. 61–69). Reston, Virginia: American Society of Civil Engineers.

Görler, S., Kühni, K., Bödefeld, J. (2007). *WSVPruf - ein IT-System für die Bauwerksinspektion nach VV-WSV 2101* (No. 4/2007). Karlsruhe.

Haimes, Y. Y. (2018). Risk Modeling of Interdependent Complex Systems of Systems: Theory and Practice. *Risk Analysis : An Official Publication of the Society for Risk Analysis*, *38*(1), 84–98.

Harteveld, C. (2011). *Triadic Game Design: Balancing Reality, Meaning and Play*. London: Springer-Verlag London Limited.

Hosseini, S., Barker, K. (2016). Modeling Infrastructure Resilience using Bayesian Networks: A Case Study of Inland Waterway Ports. *Computers & Industrial Engineering*, *93*(7), 252–266.

Johansson, J., Jonsson, H., Johansson, H. (2007). Analysing the Vulnerability of Electric Distribution Systems: A Step towards Incorporating the Societal Consequences of Disruptions. *International Journal of Emergency Management*, *4*(1), 4–17.

Jüpner, R., Bachmann, D., Fekete, A., Hartmann, T., Pohl, R., Schmitt, T., Schulte, A. (2018). Resilienz im Hochwasserrisikomanagement. *KW - Korrespondenz Wasserwirtschaft*(11), 656–663.

Kahneman, D., Klein, G. (2009). Conditions for Intuitive Expertise: A Failure to Disagree. *The American psychologist*, *64*(6), 515–526.

Kankanamge, N., Yigitcanlar, T., Goonetilleke, A., Kamruzzaman, M. (2020). How can Gamification be incorporated into Disaster Emergency Planning? A Systematic Review of the Literature. *International Journal of Disaster Resilience in the Built Environment*, *11*(4), 481–506.

Kasurinen, J., Knutas, A. (2018). Publication Trends in Gamification: A Systematic Mapping Study. *Computer Science Review*, *27*, 33–44.

Kotov, V. (1997). *Systems of Systems as Communicating Structures* (Vol. HPL-97-124).

Kourounioti, I., Kurapati, S., Lukosch, H., Tavasszy, L., Verbraeck, A. (2018). Simulation Games to Study Transportation Issues and Solutions: Studies on Synchromodality. *Transportation Research Record: Journal of the Transportation Research Board*, *2672*(44), 72–81.

Kurapati, S., Kourounioti, I., Lukosch, H., Bekebrede, G., Tavasszy, L., Verbraeck, A., . . . Lebesque, L. (2017). The Role of Situation Awareness in Synchromodal Corridor Management: A Simulation Gaming Perspective. *Transportation Research Procedia*, *27*, 197–204.

Kurapati, S., Lukosch, H., Verbraeck, A., Brazier, F. M. T. (2015). Improving Resilience in Intermodal Transport Operations in Seaports: A Gaming Approach. *EURO Journal on Decision Processes*, *3*(3-4), 375–396.

Leacock, M. (2008). *Pandemic*. Board game.

Likert, R. (1932). A Technique for the Measurement of Attitudes. *Archives of Psychology*(22), 44–55.

Lipp, U., Will, H. (2008). *Das große Workshop-Buch: Konzeption, Inszenierung und Moderation von Klausuren, Besprechungen und Seminaren* (8th ed.). Weinheim and Basel: Beltz Verlag.

Lukosch, H. K., Bekebrede, G., Kurapati, S., Lukosch, S. G. (2018). A Scientific Foundation of Simulation Games for the Analysis and Design of Complex Systems. *Simulation & Gaming*, *49*(3), 279–314.

Meijer, S. (2009). *The Organisation of Transactions: Studying Supply Networks using Gaming Simulation* (1st ed., Vol. v.6). Wageningen: Wageningen Academic Publishers.

Miles, M. B., Huberman, A. M., Saldaña, J. (2020). *Qualitative Data Analysis: A Methods Sourcebook* (4th ed.).

Niederberger, M., Wassermann, S. (Eds.). (2015). *Methoden der Experten- und Stakeholdereinbindung in der sozialwissenschaftlichen Forschung*. Wiesbaden: Springer VS.

Oliveira, C., Cintra, M., Mendes Neto, F. (2013). Learning Risk Management in Software Projects with a Serious Game Based on Intelligent Agents and Fuzzy Systems. In *Eusflat 2013*. Paris, France: Atlantis Press.

Ouyang, M. (2014). Review on Modeling and Simulation of Interdependent Critical Infrastructure Systems. *Reliability Engineering & System Safety*, *121*, 43–60.

Panenka, A., Nyobeu Fangue, F. M., Rabe, R., Schmidt-Bäumler, H., Sorgatz, J. (2020). Reliability Assessment of Ageing Infrastructures: An Interdisciplinary Methodology. *Structure and Infrastructure Engineering*, *16*(4), 698–713.

Parker, H. R., Cornforth, R. J., Suarez, P., Allen, M. R., Boyd, E., James, R., . . . Walton, P. (2016). Using a Game to Engage Stakeholders in Extreme Event Attribution Science. *International Journal of Disaster Risk Science*, *7*(4), 353–365.

Raser, J. (1969). *Simulation and Society: An Exploration of Scientific Gaming* (2nd ed.). Boston: Allyn & Bacon.

Reed, M. S., Graves, A., Dandy, N., Posthumus, H., Hubacek, K., Morris, J., . . . Stringer, L. C. (2009). Who's in and Why? A Typology of Stakeholder Analysis Methods for Natural Resource Management. *Journal of environmental management*, *90*(5), 1933–1949.

Rinaldi, S. M., Peerenboom, J., Kelly, T. K. (2001). Identifying, Understanding, and Analyzing Critical Infrastructure Interdependencies. *IEEE Control Systems*, *21*(6), 11–25.

Rodrigue, J.-P. (2020). *The Geography of Transport Systems*. Routledge.

Rüppel, U., Schatz, K. (2011). Designing a BIM-based Serious Game for Fire Safety Evacuation Simulations. *Advanced Engineering Informatics*, *25*(4), 600–611.

Shin, S., Lee, S., Judi, D., Parvania, M., Goharian, E., McPherson, T., Burian, S. (2018). A Systematic Review of Quantitative Resilience Measures for Water Infrastructure Systems. *Water*, *10*(2), 164.

Solinska-Nowak, A., Magnuszewski, P., Curl, M., French, A., Keating, A., Mochizuki, J., . . . Jarzabek, L. (2018). An Overview of Serious Games for Disaster Risk Management – Prospects and Limitations for Informing Actions to Arrest Increasing Risk. *International Journal of Disaster Risk Reduction*, *31*, 1013–1029.

Squire, K., Giovanetto, L., Devane, B., Durga, S. (2005). From Users to Designers: Building a Self-organizing Game-based Learning Environment. *TechTrends*, *49*(5), 34–42.

Taillandier, F., Adam, C. (2018). Games Ready to Use: A Serious Game for Teaching Natural Risk Management. *Simulation & Gaming*, *49*(4), 441–470.

Tang, J., Heinimann, H., Han, K., Luo, H., Zhong, B. (2020). Evaluating Resilience in Urban Transportation Systems for Sustainability: A Systems-based Bayesian Network Model. *Transportation Research Part C: Emerging Technologies*, *121*, 102840.

Tsai, M.-H., Chang, Y.-L., Shiau, J.-S., Wang, S.-M. (2020). Exploring the Effects of a Serious Game-based Learning Package for Disaster Prevention Education: The Case of Battle of Flooding Protection. *International Journal of Disaster Risk Reduction*, *43*, 101393.

Wehrle, R., Wiens, M., Schultmann, F. (2021). Application of Collaborative Serious Gaming for the Elicitation of Expert Knowledge and towards creating Situation Awareness in the Field of Infrastructure Resilience. *International Journal of Disaster Risk Reduction*.

Wehrle, R., Wiens, M., Schultmann, F., Akkermann, J., Bödefeld, J. (2020). Ebenensystem zur Resilienzbewertung kritischer Verkehrsinfrastrukturen am Beispiel der Wasserstraßen. *Bautechnik*, *97*(6), 395–403.

Wickens, C. D. (2002). Situation Awareness and Workload in Aviation. *Current Directions in Psychological Science*, *11*(4), 128–133.

Wouters, P., van der Spek, E. D., van Oostendorp, H. (2009). Current Practices in Serious Game Research. In L. Boyle, M. Stansfield, T. Connolly (Eds.), *Games-based learning advancements for multi-sensory human computer interfaces* (pp. 232–250). Hershey, Pa: IGI Global (701 E. Chocolate Avenue Hershey Pennsylvania 17033 USA).

Wouters, P., van Nimwegen, C., van Oostendorp, H., van der Spek, E. D. (2013). A Meta-Analysis of the Cognitive and Motivational Effects of Serious Games. *Journal of Educational Psychology*, *105*(2), 249–265.

Young, M. F., Slota, S., Cutter, A. B., Jalette, G., Mullin, G., Lai, B., . . . Yukhymenko, M. (2012). Our Princess Is in Another Castle. *Review of Educational Research*, *82*(1), 61–89.

Zagal, J. P., Rick, J., Hsi, I. (2006). Collaborative Games: Lessons Learned from Board Games. *Simulation & Gaming*, *37*(1), 24–40.

Zio, E. (2016). Challenges in the Vulnerability and Risk Analysis of Critical Infrastructures. *Reliability Engineering & System Safety*, *152*, 137–150.

Žnidarič, A., Pakrashi, V., O'Brien, E., O'Connor, A. (2011). A Review of Road Structure Data in Six European Countries. *Proceedings of the Institution of Civil Engineers - Urban Design and Planning*, *164*(4), 225–232.

F Measuring systemic and cascading risk of transport infrastructure based on a systemic approach and input-output modelling using the example of waterways

Abstract[1]

Purpose - The aim of this paper is the assessment of systemic risks resulting from missing or misallocated repair measures of transport infrastructures taking waterways as a use case. In this context, cascading effects and risks within the systems of building structure, industry and population are considered, while risks arising from interdependent Critical Infrastructures (CIs) are of particular interest. The systemic risk assessment is implemented as a GIS-based decision tool (risk dash board) to support decision makers in a risk-based maintenance strategy.
Methodology - A framework based on a chain of interdependent risks of different levels of the system represents the base model. The interlinkages of industries are quantified by Input-Output-Modeling and the spatial dimension is implemented as a GIS-based decision tool.
Findings - From an analytical perspective, the close interconnection of the systems' levels (subsystems) under consideration can be traced and quantified. In particular, the results highlight critical buildings leading to potentially serious impacts on industry and population if the infrastructure elements are not maintained. The impact of actual cascade effects is observed to be comparatively low.
Research limitations - This research is focused on the framework and impacts on interdependent CIs, while work on the vulnerability of constructions and population protection, which complements our approach, is explored in more depth elsewhere.
Practical implications - Maintenance of infrastructure elements should be more risk-based than timeoriented to avoid potential damage and reduce impacts.

[1] This chapter includes the preprint of the article "Measuring systemic and cascading risk of transport infrastructure based on a systemic approach and input-output modelling using the example of waterways" by Marcus Wiens, Frank Schultmann, and myself (Wehrle, Wiens, and Schultmann, 2022b).

Originality - The authors examine the interconnected subsystems construction, industry and population in an aggregated risk framework to quantify risks stemming from complex infrastructure interdependencies. Waterways represent an infrastructure area rarely explored in this context. Accordingly, it is important to understand the diverse and far-reaching consequences that can occur if this mode of transportation is unavailable. Implementation as a decision support tool for infrastructure operators in the form of a risk dashboard enables the integration of the approach into everyday infrastructure risk management.

Keywords: Risk, Waterways, Empirical, Input-Output-Model, GIS

F.1 Introduction

Infrastructure in all its varieties form the backbone of modern societies and constitute a complex System-of-Systems (Eusgeld et al., 2011). Transport infrastructure, as a prominent example, highlights the interconnectivities and interdependencies among infrastructure elements (Rinaldi et al., 2001) and also the vulnerability against threats of all kinds which can lead to systemic and cascading risks (Buldyrev et al., 2010). Possible threats are catastrophic events like natural disasters or terrorist attacks, but can also arise from human-technical failure, where neglected maintenance is at the center of attention.

The example of Inland Waterway Transport (IWT), a barely studied type of infrastructure, is a case in point as it demonstrates a potentially critical, systemic set of problems in the asset stocks of transport infrastructure which results in a steadily deteriorating condition of infrastructure elements. Specifically, these systemic problems stem from (1) a poor state of building structures, (2) a systemic maintenance backlog and (3) scarce or misallocated maintenance resources. Due to the systemic nature of these problems as well as the long duration and high demand for maintenance measures, improvements can only be achieved at a slow pace. However, this is precisely why a coherent risk prioritization of maintenance measures is of utmost importance.

A deteriorating transport infrastructure mostly affects the neighboring industries and other critical infrastructure (CI) within the complex System-of-Systems. For instance, cargo has to be shifted to other modes of transport, and urgently needed goods experience delivery problems.

Depending on the type of goods, different industries and CI elements can be affected in different ways, such as electricity supply, for example. Furthermore, in the case of waterways, also a threat to human life and physical well-being becomes apparent, since the settled population can be, e.g., flooded in the event of a collapsed dam.

As a consequence, neglected or misallocated maintenance of deteriorating construction assets pose a threat to both business locations and to the population (Oztanriseven and Nachtmann, 2020). These systemic risks may be exacerbated by further cascading effects, such as economic damage, which affects the population by shortages of supply, if transports are delayed or disrupted, and the endangerment of human life. As an additional economic loss category, the directly or indirectly affected population would not be available to the economy as a labor force in the worst case of extensive flooding.

Hereby, we state the key question of our research: *How can systemic risks resulting from neglected repair of infrastructure systems be assessed in a systematic and quantifiable way?* This accounts for the need to deduce where scarce maintenance resources can be deployed most efficiently. For this purpose, we develop a holistic framework to assess the systemic and cascading risks within the complex System-of-Systems of IWT. Thereby, we address the following sub-questions:

(1) How can systemic and cascading risks be assessed in a holistic framework?
(2) Are there any conceivable impacts on other CIs, which could result in cascading risks?

Our paper is structured as follows: We first deepen our motivation within a literature review about the risk assessment of transport infrastructure and the interdependencies towards interdependent CIs in the following section. Based on this, we develop a methodological framework that allows for the integration of empirical tools to assess systemic and building-specific risks in Section F.3.2. We consider the interdependencies of IWT damages towards connected CIs using Input-Output Models (Section F.3.3). The developed methodology is applied to a case study in Germany in Section F.4. to highlight the feasibility and relevance of the approach. In the same section we also present the risk dashboard, a decision support tool for infrastructure providers. Finally, we elaborate on the findings and conclude with a critical discussion.

F.2 Literature Review

F.2.1 Risk assessment of transport infrastructure systems

F.2.1.1 Inland Waterway Transport

A fundamental notion is the definition and significance of Inland waterway transport (IWT). We focus on Germany as an example region, while IWT is of great importance in nearly every country of the world (Oztanriseven and Nachtmann, 2020; Rohács and Simongáti, 2007), including hinterland transports (Hintjens et al., 2020). Approximately 18 million tons of goods are transported on German waterways monthly (Federal Statistical Office of Germany, 2019), while further existing capacity reserves must be used in the future to shift traffic from road to IWT, since it is a comparatively environment-friendly mode of transport (Rohács and Simongáti, 2007). IWT thus represents an elementary component of German and European logistics chains that at the same time serves regional water management in the areas of drinking and service water supply, irrigation, power plant utilization and wastewater disposal, as well as flood protection for the riparians. Furthermore, waterways fulfill an ecological biotope function and have a high recreational value for people (Oztanriseven and Nachtmann, 2020).

As mode of transport, IWT is seen as reliable when it is in normal operation (Federal Ministry for Digital and Transport, 2019). Normal operation in this context assumes the full functionality of the infrastructure and thus of all structures involved, for which predominately government and administration is responsible. However, structures that are system-relevant for the operation of inland navigation are in an increasingly poor condition. They are characterized by a massive maintenance backlog caused by a long-lasting investment deficit (Federal Ministry for Digital and Transport, 2019). In 2015, for example, around 85 percent of locks, 73 percent of weirs and 87 percent of pumping stations were in an inadequate state of repair (Federal Ministry for Digital and Transport, 2015).

F.2.1.2 Critical Infrastructure and risks

IWT are part of the critical infrastructures (CIs) that provide fundamental services that are substantial to the safety as well as economic and social welfare of a society (Rinaldi et al., 2001). Referring sectors are depicted in Figure F.1, while the term CI requires a delimitation of the terms criticality and risk, which is done subsequently.

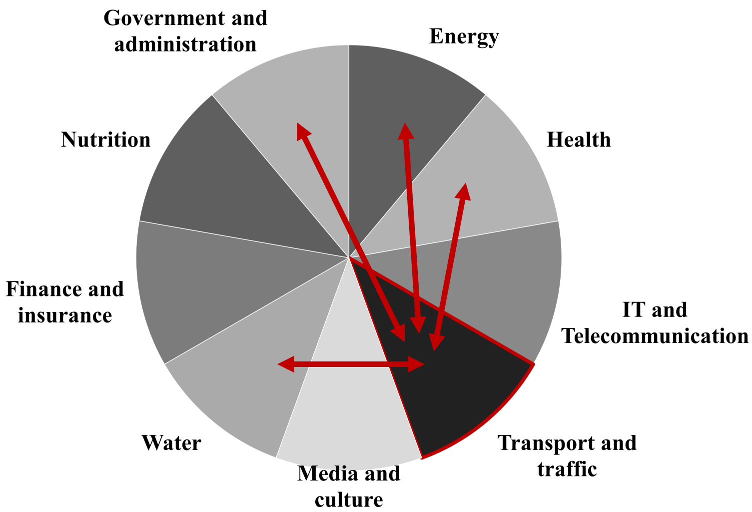

Figure F.1: Critical Infrastructures and interdependencies
(Wehrle et al., 2020)

In the field of technology and security research, the term risk is composed of the probability of occurrence and the potential consequences of a damaging event (Hauptmanns et al., 1987; Beer and Ziolkowski, 1995). The probability of occurrence is closely linked to the concept of vulnerability. Vulnerability refers to the hazard-specific susceptibility of a system to impairment or failure of its functionality, resulting in critical consequences (Lenz, 2009). The corresponding criticality, on the other hand, refers exclusively to the consequences of a system failure, independent of the probability of occurrence (Fekete, 2011).

The resilience of a system in turn describes its ability to cope with a sudden stress caused by a disruption in the system and to restore its ability to function and act as quickly as possible. This can be measured by analyzing quality and performance parameters, taking into account the recovery time (Ayyub, 2014).

Infrastructure and risk can basically interact in two ways: Risks may arise from infrastructure as well as infrastructure can be threatened by risks. Within interdependent systems, both modes of interaction are closely linked, whereas interdependencies can be of different dimensions (Rinaldi et al., 2001). Interrelations between the focused sector "Transport and traffic" are highlighted in Figure F.1, according to Wehrle et al. (2020) and the previous elaborations on IWT (Section F.2.1.1).

CI-relevant risks can be classified into (1) natural disasters, (2) terrorist attacks or (3) human-technical failure, while in the case of IWT (2) is considered rather unlikely and (1) poses a threat especially in connection with a deteriorated and vulnerable construction asset, which is namely the third classification. Therefore, we focus on the latter with its special case of neglected maintenance. Nevertheless, the three identified classifications reveal a seemingly unlimited potential of cascading effects. To analyze risks from a system's perspective, we focus on risks directly affecting IWT or going from IWT failure to subsequent CI functions (Figure F.1).

F.2.1.3 Risk assessment of CI

The challenge for risk assessment of infrastructure systems is that consequences can occur at multiple subsystems of the System-of-System infrastructure – from the construction to the industry to the population. Furthermore, various dimensions of criticality have to be considered, such as the economic, the structural, the social as well as the ecological dimension (Federal Ministry of the Interior and Community, 2011). These challenges must therefore be addressed with interdisciplinary research and require a combination of different scales and units of measurement with regard to criticality.

Theoharidou et al. (2009) provide a methodology for a risk-based criticality analysis to quantify the risk in case of failure of a CI, based on vulnerability, criticality and probability of occurrence of a hazardous scenario. They first identify elements of CI and categorize their relations and dependencies with and from other CIs, before they analyze impact factors on criticality. These impact factors are categorized in terms of scope, severity, and time and focus more on societal impacts than on internal consequences, while the scenario-based quantification is done via a psychometric 4-point Likert scale, which is weighted based on various literature reviews, expert opinions and statistics. The assessment of the hazard potential of the occurring scenarios in relation to the examined CI and their components includes the probability of occurrence of the scenario and the extent of the hazard potential on the dependent and related networked infrastructures. The quantification of probability of occurrence and vulnerability is based on historical data, literature, or expert opinion. The final aggregated risk indicator is obtained by multiplying "impact factors", "probabilities of occurrence" and "vulnerabilities" into a criticality risk factor (CRF), according to Exp. F.1 (Theoharidou et al., 2009). However, due to the simple multiplication of the factors, the analysis can result in midleading results. In addition, the choice of impact factors is crucial to the results.

$$CRF_i = Probability\ of\ occurrence \cdot Vulnerability \cdot Impact\ Factor \qquad \text{(Exp. F.1)}$$

Utne et al. (2011) use the parameters frequency, probability, extent and duration to assess the risk of CI, assuming an infrastructure failure as an initializing scenario leading to a subsequent loss of one or more "societal critical functions" (SCF). They use risk matrices to identify hazardous scenarios and analyze relevant ones in depth, taking into account location-specific and functional interdependencies, before quantifying the relevant functions based on the aforementioned parameters (Utne et al., 2011). This methodology requires detailed analyses of each scenario but attaches excessive importance to the factors frequency and probability, since this requires large amounts of historical data, which is rather scarce.

Ukkusuri and Yushimito (2009) assess the criticality of highway transportation networks using foremost methods from graph theory. As a measure of the criticality of individual components of the network, they choose the impact of the failure of an element on the individual travel time, based on the assumption that the performance of a transportation network depends largely on congestion effects caused by the interaction of traveler behavior and the built environment (Ukkusuri and Yushimito, 2009). Hence, criticality is focused on industrial criticality if transferred to IWT.

Another attempt to assess criticality of transport infrastructure is provided by Novotný et al. (2015), who analyze railway infrastructure in the network context and take into account the interactions of different CI sectors. Evidently, the methodology is strongly tailored to railways and not directly transferable to waterways, since the rail network is characterized by more redundancies and a direct dependence on power grids.

Further, rather qualitative approaches for risk and criticality assessment of infrastructure can be found in Katina and Hester (2013) or Federal Ministry of the Interior and Community (2009), for example. Nevertheless, the latter neglect the vulnerability (cf. next section) of construction elements as essential part for risk assessment and the importance to prioritize and carve out effective maintenance measures.

There are just few approaches, which come close to our research objective, the assessment of systemic risks resulting from neglected maintenance of infrastructure systems, especially IWT. Among the notable exceptions is Oztanriseven and Nachtmann (2020), who also study the system of IWT in the US, which is characterized by complexity and uncertainty. They use a multimethod approach, including agent-based modeling, discrete event simulation, system dynamics, and multiregional input–output analysis, and provide a data-intense model that nevertheless neglects business decisions.

Conversely, our research aims to provide a holistic risk assessment framework that enables the integration of interdisciplinary research aspects from fields like vulnerability of construction elements, network research and economic expertise as well as civil protection.

F.2.1.4 Risk as process chain and systemic interrelations

Based on the aforementioned explanations, risk can be considered as a process chain that is run through in each individual potentially affected system (illustrated by Figure F.2). The following elaborations are adapted from Wehrle et al. (2020). Basically, an event triggers the process chain, representing a hazard for the system. An event has a certain impact on the system depending on its vulnerability. Depending on its criticality, the system responds with consequences that are reflected in the form of potential functional failures.

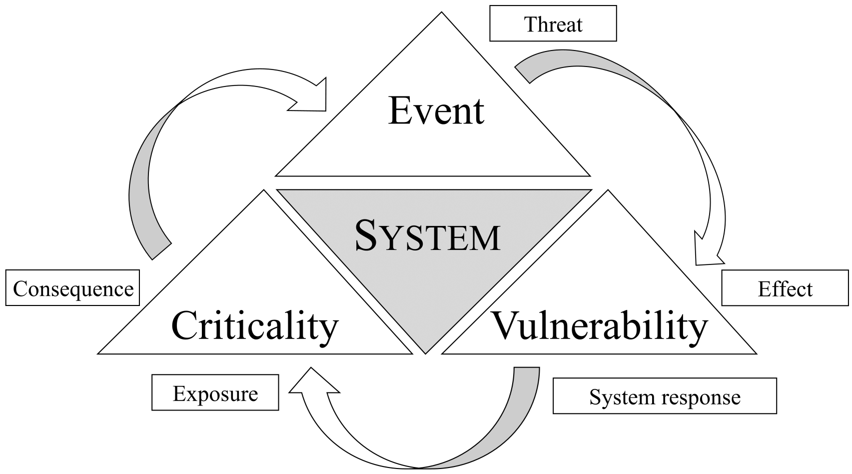

Figure F.2: Risk as process chain
(Wehrle et al., 2020)

The risk process chain (Figure F.2) can unfold at differing *levels of systems* (subsystems). For example, two distinctive characteristics of IWT are bulk cargo transportation and the potential direct exposure of the population to flooding, which is why it can be considered a System of Systems from a risk perspective, consisting of the interconnected subsystems *building*, *infrastructure network*, *industry*, and *population*, whereas each system is characterized by its vulnerability and criticality.

Consequences that occur can in turn be events that trigger the next process chain at a downstream level of the different subsystems. According to Figure F.2, these systems react to an event through the respective system-specific factors of vulnerability and criticality. Figure F.3 illustrates the fundamental concept of the System-of-System, where the events shown denote functional failures of the various systems as interfaces between the subsystem. Consider the worst case scenario of a dam breach as an example. Here a vulnerable element is washed out by a scenario of heavy rainfall and thus loses its water-retaining and consequently its traffic-relevant function. This in turn leads to the activation of the subsequent subsystems *industry* and *population*, whereby the population is threatened by flooding depending on the vulnerability of adjacent settlements. The industry must acquire alternative transport routes and modes depending on its vulnerability, although it may also be directly affected by flooding.

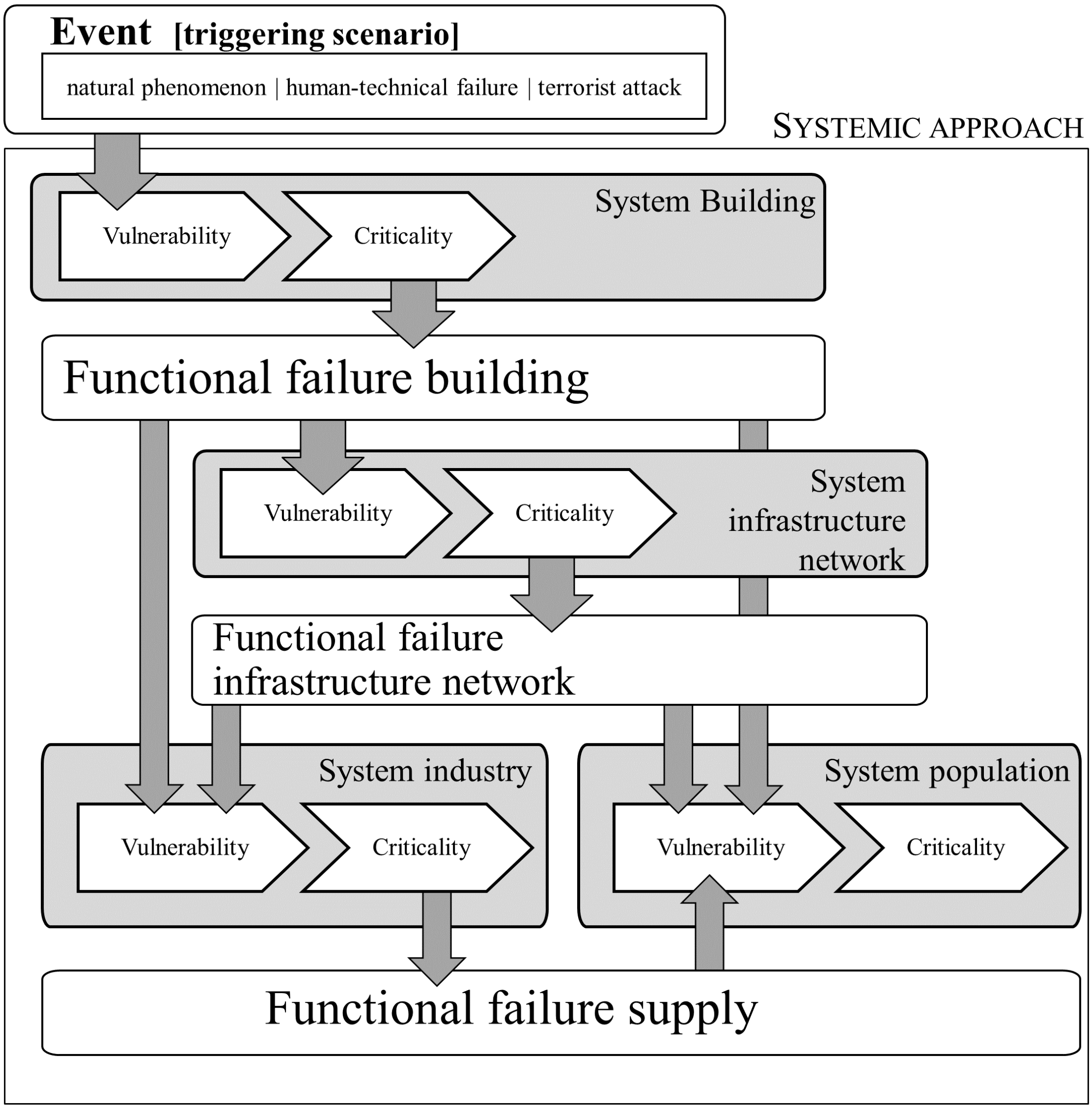

Figure F.3: Systematic risk assessment of IWT as System-of-systems

F.2.2 Supply Chain Management and dependency on transport infrastructure

To assess threats arising from disrupted Supply Chains (SCs; subsystem *industry*; Figure F.3) and concerning the subsystem *industry* via interconnected CIs, economic vulnerability and criticality must be understood to identify the most effective measures for strengthening the infrastructure. In the following, we elaborate on impacts of disrupted transport infrastructure on SCs and on the behavior of interconnected CIs towards disruptions.

F.2.2.1 Impact of transport disruptions on business activities

Impacts of IWT disturbances can cause high economic damage, such as blockades of the Suez Canal (Huth and Romeike, 2016), while impacts of disrupted SCs can be classified in (1) direct, i.e. physical damages, and (2) indirect effects, which include all types of ripple effects. Whereas direct effects in a water-related context rather arise from floods, since the effects include destroyed inventory or machines, infrastructure failure is assigned to the indirect effects (Haraguchi and Lall, 2015).

Companies may react by adapting their SC structure, choice of transportation routes and means (Craighead et al., 2007), increasing SC visibility, enhancing buffer capacities or by considering the use of more generic input components (Ivanov and Dolgui, 2019; Lücker et al., 2019; Fujimoto, 2011). While alternative routing may be sufficient for short-term disruptions, there is in most cases no feasible solution in the long-term such as shifting IWT cargo towards other means of transport, which are regularly capacity-restricted. Moreover, for specific goods it is possible to become independent from public infrastructure, as via own pipelines (Park et al., 2013). However, for most industries and goods this is no feasible option, making relocation a possibility as well (Farahani et al., 2009), since reliable transport infrastructures plays an important role in companies' location decisions (Mejia-Dorantes et al., 2012; Rezaei et al., 2018).

F.2.2.2 Disruptions in interconnected sectors

Given the high degree of interconnectedness of today's supply chains, disruptions in one sector affect other sectors, which may have to wait for input factors or experience extreme volatility in demand. Since sectors and CIs are highly interdependent and interrelated, as discussed in the previous sections, these interdependencies need to be analyzed and evaluated to assess the risks arising from disruptions in individual sectors or CIs. This addresses our sub-question *(2) Are there any conceivable impacts on other CIs, which could result in cascading risks?*

Methods to quantify the economic damage that can result from interdependencies among sectors include agent-based models (Barton and Stamber, 2000; Balducelli et al., 2005), dynamic general equilibrium models (Zhang and Peeta, 2014), hierarchical holographic modeling (Haimes, 1981), high-level architecture (Grogan and de Weck, 2018), and input-output models (Hallegatte, 2008), among others (Ouyang, 2014). Agent-based models are based on a group of dynamic, rule-based interacting agents. In doing so, such models can represent complex behavioral patterns from which information for the real world can be inferred. Dynamic general equilibrium models can be used to formally describe the equilibrium behavior of sectors and their underlying economic structures, such as complex market systems, over time. Hierarchical holographic modeling attempts to understand risks in the different levels of the hierarchy. There is a holographic viewpoint, which means that multiple parts of the system are used to discover vulnerabilities. In the high level architecture method, the overall system is divided into smaller subsystems that are individually operable as simplification which attempts to understand complex systems (Eusgeld et al., 2011).

Besides the methods mentioned above, a valuable tool in economic statistics on national accounts is the Input-Output-Model (IOM), which systematically records sector-vise supply-demand-relationships of regional and national economies (Leontief, 1986). As a prognostic tool it even allows successful forecasts of the economic development of companies . Moreover, an evolution of the IOM is the Inoperability-Input-Output-Modell (IIOM) (Haimes and Jiang, 2001) which allows to assess (1) impacts of disrupted sectors on other sectors as well as (2) impacts of disrupted transport infrastructure as an underlying sector to interdependent sectors.

F.3 Research Methodology

F.3.1 Concept

We derive a framework for measuring risks that operate at different, interconnected subsystems, based on Wehrle et al. (2020), as described in Section F.2.1.4. The detailed concept and process of risk assessment is explained in Section F.3.2. Moreover, we use a supply-side IIOM to assess cascading effects of infrastructure failure on interdependent CIs in Section F.3.3.

F.3.2 Framework

F.3.2.1 Processes of developed framework

The framework evaluates building-specific risks in order to enable a risk-based maintenance prioritization. Ultimately, as the risk-based consequences of an aging building stock spread across systems with, at the same time, severely limited resources for risk prevention, a holistic and systemic risk assessment is carried out and maintenance measures can thus be allocated where the risks are greatest.

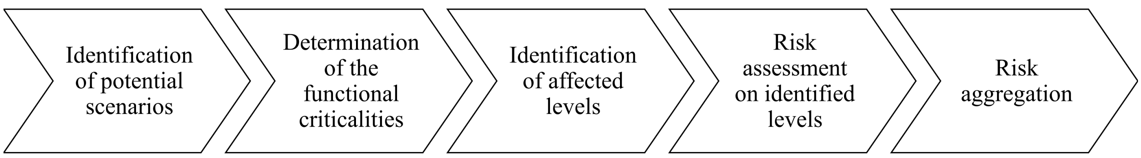

Figure F.4: Procedure of risk assessment

The risk assessment is based on the System-of-Systems depicted in Figure F.3, while Figure F.4 illustrates the operational procedures of risk assessment, starting with step 1, the identification of potential scenarios for object categories and, derived from this, for individual infrastructure elements. Subsequently, the functional criticalities are derived (step 2), i.e., which functions an infrastructure element fulfills in its normal state and which functions could be restricted as a result in the entire transport network if the infrastructure element fails (Table F.1). These functions are adopted from (Federal Ministry for Digital and Transport, 2014b) according to Wehrle et al. (2020), stating that failures of the depicted building functions affect the functionalities of the subsystem network. One example of this is the failure of a feed pumping station facility, which primarily serves the functions “water level regulating” (wlr) and “traffic-relevant” (tr). Its failure leads to impairments of the traffic function in the whole connected canal network, but not to a failure of the water-retaining (wr) function, as it would be in the case of a safety barrier gate: here, a failure of the building function “water-retaining” (wr) also causes an impairment of the water-retaining function of a whole canal pound and thus also activates the category “traffic relevance”.

	Function of network	
Function of building	**water-retaining**	**traffic-relevant**
water-retaining (wr)	×	×
water level regulating (wlr)	×	×
traffic-relevant (tr)		×
securing (s)	×	×
transversal (t)	×	×

Table F.1: Interdependencies of functions

This chaining logic from Table F.1 is used to identify the affected subsystems (Step 3): If the water-retaining function of the network is potentially at risk, the subsystems industry and population are affected. For example, in the case of a dam breach no shipping is possible without water in the canal (disrupted transportation causes economic loss for the subsystem industry) and the population is threatened by flooding (leading to potential harm for health or life for the subsystem population). If, on the other hand, only the traffic-relevant function is threatened, the risk analysis just takes the effects on the subsystem industry into account.

Step 4 concludes with the assessment of risk and its components on the identified subsystems. On the level of the subsystem building the vulnerability of the building objects is determined, considering the robustness of construction structures against safety scenarios: Low vulnerability structures are characterized by high robustness to the safety scenarios, whereas a structure with major damage and poor condition constitute a more vulnerable structure (Figure F.5).

The risk assessment methods for the individual systems are not described here in detail due to the scope of this paper but details can be found within the account of Wehrle et al. (2020), Akkermann et al. (2020), Akkermann et al. (2018) and Hüttelmaier et al. (2019). In general, the methodologies of the subsystems industry and population incorporate the assessment of the consequences in the event of a damage.

The subsystem industry exhibits vulnerabilities with respect to inadequate supply chain redundancies, which refer, for example, to alternative transport routes to IWT. Here, in particular the economic criticality is determined and evaluated. Criticality arises primarily from detour and downtime costs of unrealized productions or deliveries. Moreover, supply failures can represent a triggering event of the risk process chain in the population system as functional supply failure

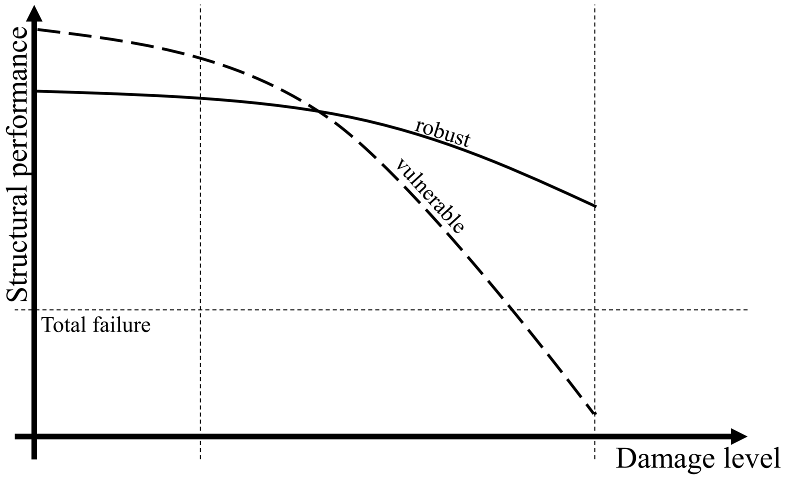

Figure F.5: Damage sensitivity for vulnerable and robust structures (Akkermann et al., 2018)

(Figure F.3). An example is the throttling of a power plant because the required coal can no longer be transported via the canal (in time).

The connected subsystem population faces threats from the described interdependence on the industry but can also be directly affected by IWT disruption. A specific case here is the aforementioned breach of a dam, which endangers human life due to the risk of flooding settlements.

The aggregation to criticality (Step 5), i.e. the final consequences of the logic chain, is then carried out via a two-stage weighting, which, by including the vulnerability, leads to the final risk determination for a specific infrastructure building as construction asset.

F.3.2.2 Risk assessment

The aggregation towards a consistent risk assessment is conducted via s scenarios per building b, considering each of the identified relevant subsystems (Step 3, Figure F.4), according to the following formula based on Hodges-Lehmann (Hodges and Lehmann, 1952; Turskis et al., 2009):

$$Risk_b = \alpha \cdot \sum_s u_{bs} p_{bs} + (1-\alpha) \cdot \max_s \{u_{bs}\} \qquad \text{(Exp. F.2)}$$

The expression incorporates the stakeholder's disutility $\mathrm{u_{bs}}$, which reflects the risks for industry and population. While the left term of Exp. F.2 represents the decision maker's expected utility, the right-hand part supplements the assessment with a pessimistic estimate according to the Wald-rule, which considers the worst case and thus the maximum risk. The values for $\alpha, \beta \in [0;1]$ can be determined by the decision maker: $\alpha = 1$ (decision maker is an expected utility maximizer with a neutral attitude towards ambiguity) implies a purely balanced and equally weighted consideration of the different damage scenarios of the structures), and $\alpha = 0$ (extremely pessimistic and ambiguity-averse decision maker) considers only the worst-case scenario in the calculation. The weighting parameter β allows for goal prioritization between commercial (industry) and civil protection (population):

$$u_{b,s} = \beta \cdot Risk_{Industry,b,s} + (1-\beta) \cdot Risk_{Population,b,s} \quad \text{(Exp. F.3)}$$

Furthermore, a scenario-specific, structure-immanent vulnerability of the construction structure $\mathrm{p_{b,s}}$ as approximation of the probability of occurrence is normalized and included:

$$p_{b,s} = \frac{Vulnerability_{bs}}{V_{\max} \cdot s_{\max,b}} \quad \text{(Exp. F.4)}$$

The values for vulnerability and risk are determined in the value range $[0; 5]$, resulting in $\mathrm{V_{max}} = 5$.

F.3.2.3 Visualization of results as a risk dashboard

The methodology results in risk assessments of specific construction assets and provides decision support for the difficult but important task of prioritization of maintenance measures. It is implemented in a programmable environment, built on editable databases, which also incorporate spatial data. Thus, a GIS-based visualization can serve to communicate the results to decision makers and the extended group of stakeholders. Moreover, the GIS-tool must incorporate (1) a quick view of the results, triggering known assets of the decision-makers, (2) easily accessible background information and (3) the possibility to adjust preferences (α, β).

F.3.3 Risk for interdependent CI

The IIOM (cf. Section F.2.2.2) provides a method to assess the impact of a failure in one CI towards interdependent Cis, which can serve to answer our sub-question 2 (*Are there any conceivable impacts on other CIs, which could result in cascading risks?*). To apply this in the context of our framework, we briefly explain the basic features of the IOM before moving on to explain the methodology and functionality of the IIOM.

F.3.3.1 Input-Output Model

The flows of goods in an economy can be represented by the Gozintograph in Figure F.6, where the arrows indicate the commodity flows consumed in other sectors and in the origin sector. Input-output tables are used to represent these relationships mathematically, assuming that total inputs equal total outputs.

The basic formula of the IOM (Leontief, 1986) is given by Exp. F.5, briefly modified to Exp. F.6, showing that production and consumption are linearly related by $[\mathrm{I} - \mathrm{A}]^{(-1)}$ and that a change in final demand influences the total production. Hereby, A is the technical coefficient matrix,

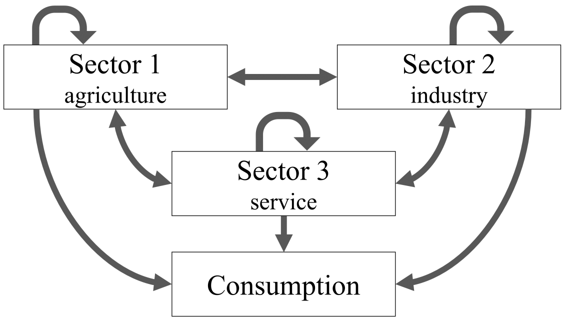

Figure F.6: Flows of goods as basis for IOM
(cf. Grubbstrom and Tang, 2000; Vazsonyi, 1954)

consisting of a_{ij} from sector i to sector j and I is the Unit matrix. X and x_i refer to the production (matrix) and C and c_i accordingly refer to the demand.

$$x_i = \sum_{j=1}^{n} a_{ij} x_j + c_i \quad \text{(Exp. F.5)}$$

$$X = [I - A]^{-1} \times C \quad \text{(Exp. F.6)}$$

Furthermore, the analysis of backward and forward linkages enables the identification of key sectors, depending on the effect index RB_j and sensitivity RF_j of sectors (Kula, 2008; Chenery and Watanabe, 1958; Hirschman, 1958):

$$B = [I - A]^{-1} \quad \text{(Exp. F.7)}$$

$$RB_j = \frac{\sum_i b_{ij}}{\frac{1}{n}\sum_i \sum_j b_{ij}} \quad \text{(Exp. F.8)}$$

$$RF_i = \frac{\sum_j b_{ij}}{\frac{1}{n}\sum_i \sum_j b_{ij}} \quad \text{(Exp. F.9)}$$

Based on these indices, a classification can be derived, according to Table F.2 (Temursho, 2016).

		Forward linkages	
		Low (<1)	**High (>1)**
Backward linkages	**Low (<1)**	Weak linkages sector (W)	Strong forward linkage sector (F)
	High (>1)	Strong backward linkage sector (B)	Key sector (K)

Table F.2: Classification of sectors

F.3.3.2 Inoperability Input-Output-Model

Inoperability in terms of the IIOM refers to the inability of the system to fulfill its intended function, while the basic formula for calculating the inoperability is the following according to Santos and Haimes (2004):

$$q = A' \cdot q + c' \qquad \text{(Exp. F.10)}$$

Here, q is defined as the inoperability, A' is the technical coefficient matrix and c' is a demand disturbance vector representing the reduced final demand. Thus, Exp. F.10 represents the demand-side IIOM, while another variation is the supply-side IIOM, which allows to assess disruptions in supply. The calculation of the supply inoperability p is represented by Exp. F.11 where z' is a supply disturbance vector and $A^{s'}$ is the supply interdependence matrix, according to Ocampo et al. (2016), which can be extracted from an IO table using Exp. F.12 and Exp. F.13.

$$p = (I - A^{S'})^{-1} \cdot z' \qquad \text{(Exp. F.11)}$$

$$z' = \left(diag(\widehat{x})\right)^{-1} \times (\widetilde{z} - \widehat{z}) \qquad \text{(Exp. F.12)}$$

$$A^{S'} = \left(diag(\widehat{x})\right)^{-1} \times A^{S} \times diag(\widehat{x}) \qquad \text{(Exp. F.13)}$$

The supply disturbance vector z' is calculated by multiplying a diagonal inverted matrix of the planned production $\hat{x}$ withthe difference between the planned offers $\bar{z}$ and the reduced offers$\hat{z}$. The supply interdependence matrix $A^{s'}$ is calculated using the supply-side Coefficient Matrix A^{s} and $\hat{x}$. With these results the supply inoperability p can be calculated, considering the CI sectors depicted in Figure F.1. Altogether, this provides us with the answer to our sub-question *(2) Are there any conceivable impacts on other CIs, which could result in cascading risks?*

F.4 Case

F.4.1 West German Canal Network

We apply our methodology to the area of the West German Canal Network, consisting of 350 kilometers of canals connecting the Ruhr area and the German North Sea ports (WSA Westdeutsche Kanäle, 2022). Table F.3 shows all object groups of the considered IWT infrastructure (Federal Ministry for Digital and Transport, 2014b). These objects are the basis of risk assessment, since construction elements may pose risks due to their deterioration, which in turn must be countered by a risk-based maintenance strategy. Moreover, Table F.5 shows the importance of our elaborations by specifying the number of considered objects in the studied area.

In 2013, the transport volume transported in the West German canal network amounted to approximately 226.8 million freight tons, which corresponds to 37.1% of the total waterborne transport volume in Germany (Federal Waterways and Shipping Agency of Germany, 2014). Moreover, the region of North Rhine-Westphalia (NRW) is characterized by a comparatively high population

	Object top group	Examples
100	Objects for water drainage and navigability of IWT and navigability of sea waterways	River bed (part of canal side dam) Canal bridges
200	Objects for regulating and securing the water level and for hydrological measurements	Weirs, water distribution facilities Feed pumping stations, Flood control gates Remote control central systems
300	Objects for shipping traffic	Ship lock facilities, Ship lift facilities Boat launching facilities, boat towing facilities Control centers for locks
400	Objects for securing and facilitating shipping traffic	AIS shore stations, district radio stations Nautical information radio installations
500	Objects for maintaining the crossing traffic of IWT	Culverts, dock levellers, pipe dock levelers
600	Objects for other direct tasks	Protection facilities against dilution damage Extraction and inflow structures Hydroelectric power plants, Fish passes

Table F.3: Object types West German canal network
(Wehrle et al., 2020; Federal Ministry for Digital and Transport, 2014b)

density and a significant economic importance, which was mainly backed by the coal mines and steel industry.

F.4.2 Framework

As stated in Section F.3.2, we apply the proposed framework to ultimately derive a risk-based maintenance strategy. To this end, we carry out a scenario-based risk assessment for each building, which is scenario-specific and depends on the inherent vulnerability of the system, the affected population and industry location factor, and the impact on interdependent critical infrastructure.

F.4.2.1 Risk assessment

The scenarios natural disasters, terrorist attacks and human-technical failure are analyzed as triggering events for the failure of IWT structures, whereas human-technical failure is anticipated as the most likely scenario. More detailed scenarios are identified using expert knowledge and failure-tree analysis, among others. Results and the integration into the introduced risk concept for the subsystem building are shown exemplarily in Table F.4.

Since we define individual scenarios for each building type, we exemplarily formulate the scenarios for locks as follows: (S1) heavy ice formation, (S2) equipment (e.g. bollards) not functional, (S3) stability of individual components is not given, (S4) technical equipment in poor condition, (S5) missing spare parts, (S6) average, and (S7) sabotage/vandalism of the technical equipment, whereas S2-S5 comprise human-technical failure.

	Solid construction: wall of a Lock chamber block	Steel hydraulic engineering: Weir	Geotechnics: Impoundment dam
Event	**Missed maintenance: reinforcement rusting**	**Axle breakage at a weir closure**	**Heavy rainfall**
Threat	Overstressing of reinforcement	Unscheduled position/ placement of the weir closure	High water level
Effect	Increase in load	Unscheduled load application	Water pressure and flow force during flow through
Vulnerability	**No reserves/redundancy in reinforcement**	**Closure with rollers, drive and built-in parts susceptible to deformation**	**Dam susceptible to flowthrough**
System response Building	Reinforcement failure, significant deformation increases	Jamming of the closure in guide	Dam failure
Exposure	Narrowing of chamber width, sagging of backfill, leakage	Outflow regulation no longer possible	Outflow of the water in the dam and flooding of the hinterland
Criticality	**Failure of the function traffic-relevant**	**Impairment of functions Water level regulating /water-retaining → unplanned water levels**	**Failure of the function water-retaining**
Consequences Subsequent subsystems	(Partial) closure, restriction of use	Restriction/failure traffic function	Restriction/failure of traffic function Flooding of hinterland

Table F.4: Risk concept for the subsystem "building"
(cf. Wehrle et al., 2020)

F.4.2.1.1 Determination of the functional criticalities and affected subsystems

As outlined in Section F.3.2.1, potential functional failures are derived first for the subsystem *building* (Table F.4, bottom) and subsequently for the subsystem *canal network*, since in the further systemic consideration, failures of the structure functions affect the subsequent subsystems, with the next affected subsystem being the canal network.

Table F.5 represents the functional criticalities of the considered systems. It assigns the respective functions of building and network as well as the affected subsystems (i.e. whether the subsystem *industry* and/or *population* is threatened by the risk) to the different building types (Federal Ministry for Digital and Transport, 2014b).

F.4.2.1.2 Risk assessment on identified subsystems

For the subsystem *building*, system-inherent, scenario-specific vulnerabilities of building structures must be determined as part of the risk assessment. Nevertheless, as stated in the outline of our methodology, the assessment for the subsystems *building* and *population* are not explicitly shown in this paper. It remains to say that the parameters are normalized to values between 0 and 5 and are determined on a structure-specific basis, which are illustrated exemplarily in the next section.

Obj. ID	Building type	Number of objects	Function of building					Function of network		Affected subsystems	
			wr	wlr	tr	s	t	wr	tr	Industry	Population
111	Canal side dam	327	×		×			×	×	×	×
112	Canal bridges	8	×		×			×	×	×	×
213	Weirs	2	×	×	×			×	×	×	×
221	Feed pumping station facilities	18		×	×				×		×
232	Flood barrier gate systems	1	×			×		×	×	×	×
233	Safety barrier gate	17	×			×		×	×	×	×
311	Ship lock facilities	17	×		×			×	×	×	×
510	Bridges	276					×		×		×
535	Culverts	168	×				×	×	×	×	×
537	Siphon (Düker)	238	×				×	×	×	×	×

Table F.5: Functional criticalities of objects: subsystems building and network

F.4.2.2 Risk aggregation

The details of the risk aggregation for an exemplary building is shown in Table F.6. Based on the previously identified scenarios and the collected data among the described steps, we apply formulas from Section F.3.2.1. We use $\alpha = 0.5$ (moderate degree of pessimism,) and $\beta = 0.5$ (equal weigthing between commercial and civil protection goals) as default weighting parameters.

Scenario	$\mathrm{Vuln.}_{b,s}$	$p_{b,s}$	$\mathrm{Risk}_{\mathrm{Pop.},b,s}$	$\mathrm{Risk}_{\mathrm{Ind.},b,s}$	$u_{b,s}$	$u_{b,s} \times p_{b,s}$	$\max\{u_{b,s}\}$	Risk_b
S1 – Ice	4.576	0.131	1.48	1.00	1.240	0.162	2.240	1.976
S2 – Equipment	4.538	0.130	1.48	3.00	2.240	0.290		
S3 – Stability	4.768	0.136	1.48	3.00	2.240	0.305		
S4 – Technical Eq.	4.678	0.134	1.48	2.00	1.740	0.233		
S5 – Spare parts	4.678	0.134	1.48	1.00	1.240	0.166		
S6 – Average	5.000	0.143	1.48	3.00	2.240	0.320		
S7 – Sabotage	4.753	0.136	1.48	2.00	1.740	0.236		

Table F.6: Calculation of risk for building b: ship lock Gelsenkirchen, south chamber

Specific data originates from assessments of building vulnerability $(\mathrm{Vuln.}_{b,s})$, civil protection $(\mathrm{Risk}_{\mathrm{Pop.},b,s})$, and empirical research for the acquisition of data for $\mathrm{Risk}_{\mathrm{Ind.},b,s}$ as economic risk potential, which is not described here in further detail.

F.4.2.3 GIS application and risk dashboard

F.4.2.3.1 User Interface

Risk assessment and aggregation is performed for each building in the modelling region and the results are illustrated within a GIS and web-based application, which also allows for a ranking as risk-based dashboard for maintenance-prioritizing. Since the tool is developed for national application, the following screenshots of the tool depict the current version in German language.

As Figure F.7 shows, the application meets the requirement of displaying selected risk-relevant buildings, but also other structures for which no risk assessment has been conducted, as they have been classified as non-risk relevant. Various background maps and further data visualizations, such as flood hazard maps, allow for a rich individual information potential of the tool. A mouse-over also provides a quick overview of the local structures.

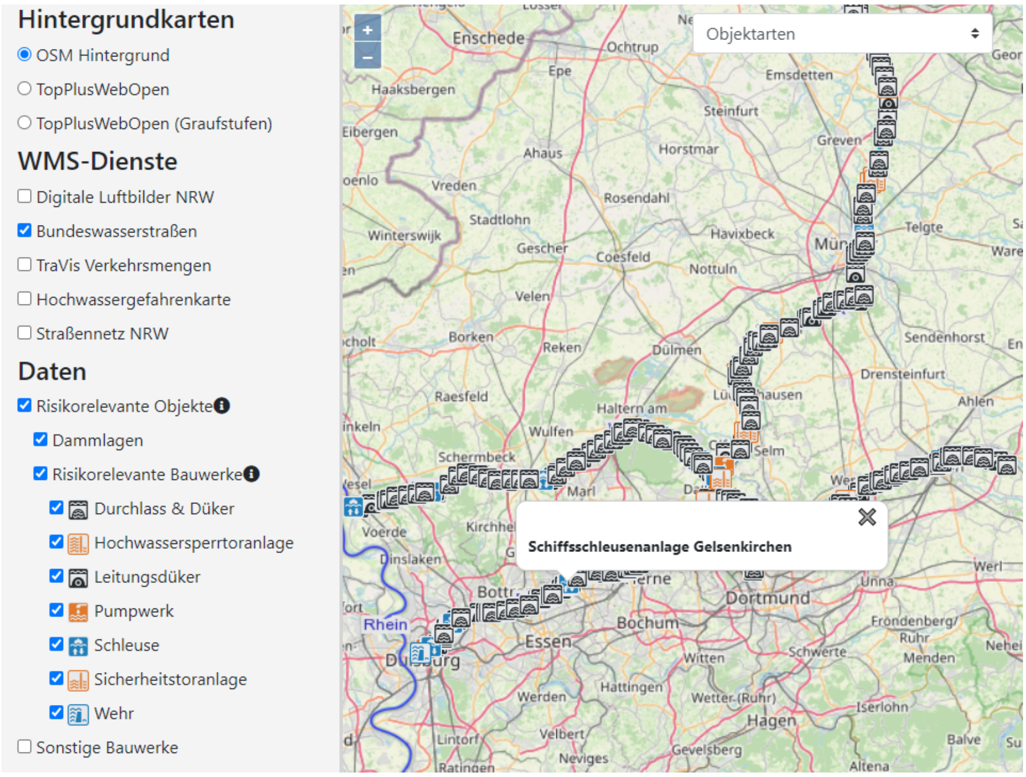

Figure F.7: Tool overview

By selecting a specific building, the user obtains more information about the building and its risk assessment, as Figure F.8 shows. Further buttons lead to a pop-up for visualizing the details of the risk assessment with a chart comparing logistic and population risks of specific scenarios (Figure F.8, bottom left) as well as to a pop-up of the listing of possible resilience-enhancing measures (Figure F.8, top right). In addition, the average vulnerability across the scenarios is presented, for which again a scenario-specific explanation is available (Figure F.8, bottom right). The overall risk is visualized by color next to the total risk value.

Figure F.9 illustrates how the applications allows to display all risk relevant objects in the system with a color indicating the risk category according to their vulnerability and economic and civil risk potential, while sliders can be used to adjust the weightings (α, β). The result is the risk-based prioritization of buildings that are subject to potential maintenance measures. By clicking on the object ID (Figure F.9), the GIS tool navigates directly to the respective building, which enables a direct view on the detailed data and thus provides transparent and easy to use decision support for the prioritization of maintenance measures by infrastructure operators.

F.4.2.3.2 Technical realization

The application is entirely based on opensource components for the provision and visualization of geodata via the Internet. The open Javascript library OpenLayers is used, which enables the platform-independent visualization of geodata in the web browser. Geodata is stored file-based in GeoJSON format, so that the application can access it directly. The application is provided by a web server (e.g. Apache, Nginx) and offers the possibility to publish the contents in the internet.

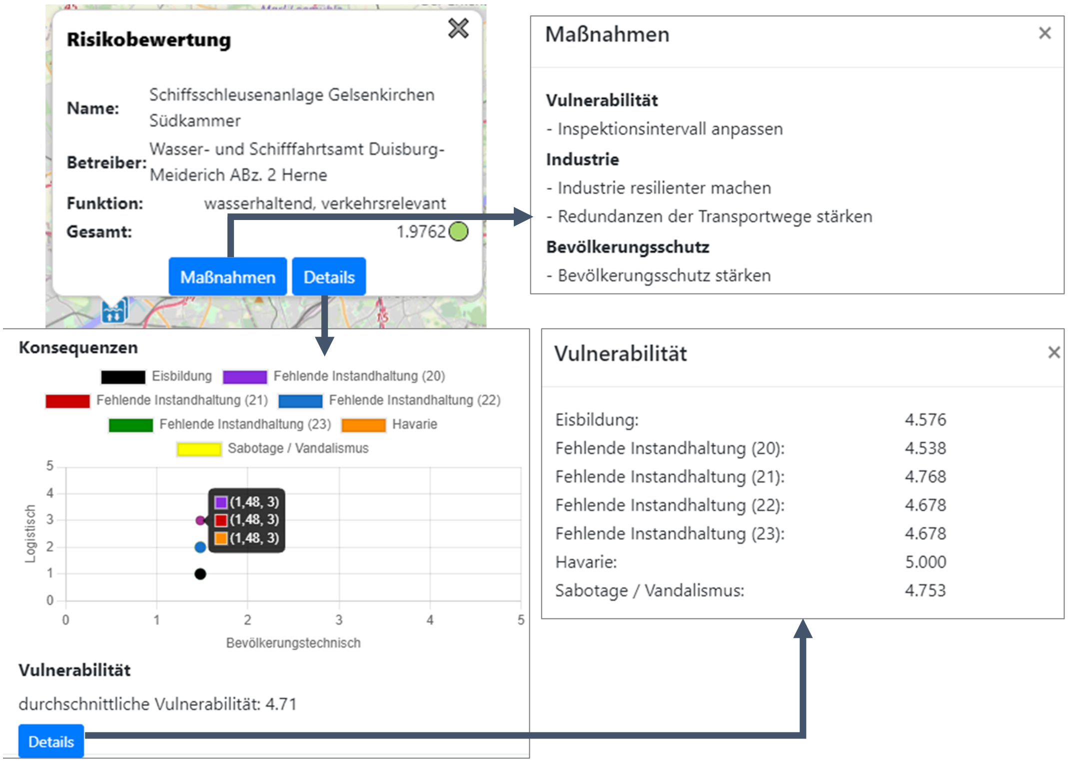

Figure F.8: Illustration of risk assessment in GIS-Tool

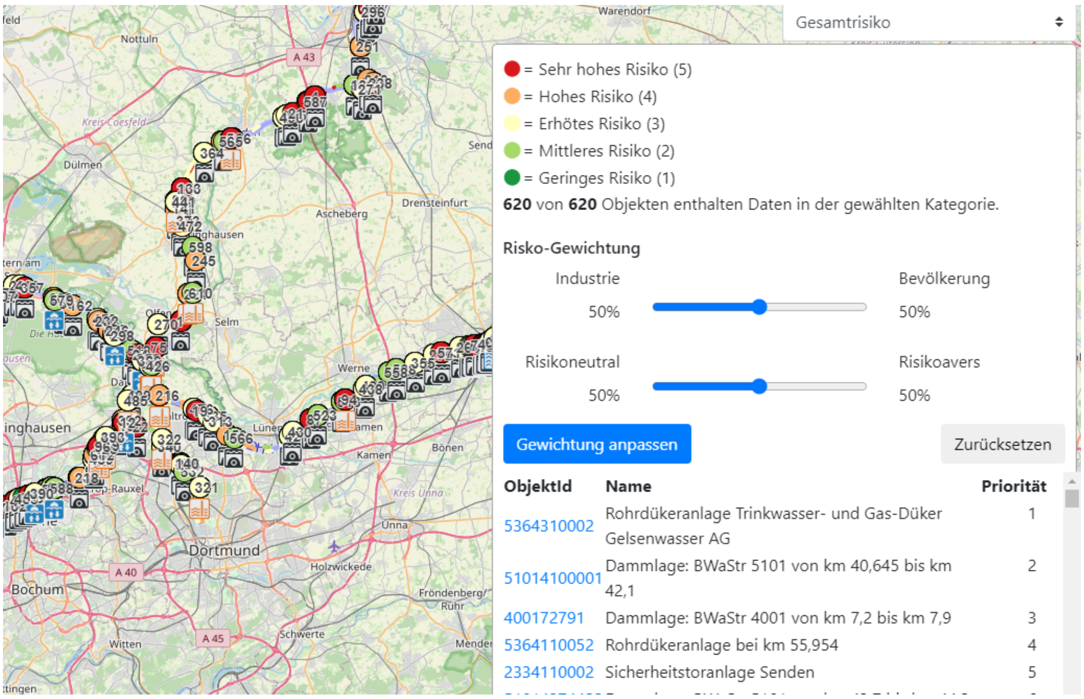

Figure F.9: Layers and prioritizing

F.4.3 Impact of IWT disruptions on interdependent CI

In the next step, we analyze interdependencies among CI with respect to an input-output analysis as introduced in Section F.3.3.

F.4.3.1 Interdependent CI

IWT on rivers, canals and lakes for the transport of goods and passengers represent an important part of the German water transport system. In 2019, IWT carried 4.3% of the total transport volumes, around 205 million tons of goods, with the volume of goods increasing by 3.6% compared to the previous year (Federal Statistical Office of Germany, 2021).

Moreover, the analysis of the impact of IWT disruptions on interdependent CI requires a closer look at the local situation. NRW has the highest share of total cargo handling in Germany at 47.2% with Table F.7 showing the shares of most significant commodity groups of IWT.

Goods Groups	**Tons**	**Share**
Ores, stones and earths	2 609 065	29.3%
Coke and mineral oil products	1 741 386	19.6%
Coal; crude petroleum and natural gas	1 158 275	13.0%
Chemical products	968 211	10.9%
Products of agriculture and forestry	414 767	4.7%
Total	8 896 717	100%

Table F.7: Total IWT by freight division in NRW in January 2020 (cf. Federal Statistical Office of Germany, 2021a)

F.4.3.1.1 Water supply

Water in Germany primarily comes from groundwater (61%), spring water (9%), surface water (12%), and bank filtrate and recharge. Groundwater is pumped from a depth of hundreds of meters to waterworks for treatment after ensuring some quality requirements and is supplemented by surface water if necessary. In the waterworks, drinking water is treated by various technical and chemical processes before being fed into the drinking water network, which in Germany has a length of 530,000 km. Subsequently, the water is transported to its destination: households and industrial consumers who are often dependent on cooling or process water.

Nevertheless, the high proportion of groundwater is not fully reflected in NRW: 16.8% of drinking water originates from surface water, as shown in Table F.8.

Origin	Germany	NRW
Ground water	61.2%	39.6%
Spring water	7.9%	2.0%
Enriched groundwater	9.3%	31.1%
Bank filtrate	8.0%	10.6%
Surface water	13.5%	16.8%

Table F.8: Origins of public water supply in Germany
(cf. Federal Statistical Office of Germany, 2018)

F.4.3.1.2 Power supply

NRW produces 30% of Germany's electricity and re-consumes about 40% of Germany's industrial electricity (Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen, 2020), because NRW is home to a major share of energy-intensive industry as well as small and medium-sized enterprises.

Different types of power generation are the focus of the sustainable energy discussion today. Therefore, the market is constantly changing and the current data on the generating mix (Figure F.10) is expected to change significantly within the next 10 years, since the last brown coal power plant is to be taken off the grid in 2038 and a phase-out of nuclear power by 2022 is planned

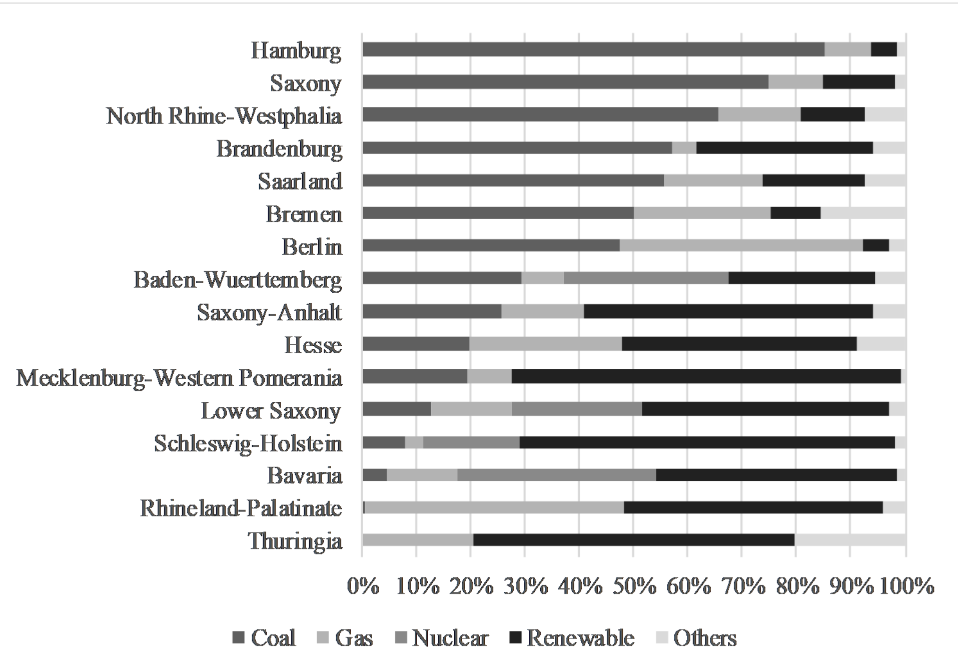

Figure F.10: Types and shares of power generation in Germany in the year 2017
(cf. Federal Statistical Office of Germany, 2017)

by the German government (Mitteldeutscher Rundfunk, 2021). Nevertheless, major sources of power generation are still dependent on coal and gas (Figure F.10).

F.4.3.1.3 Cooling Water

Conventional thermal power plants require cooling of the operating medium, usually steam, which is realized via cooling water by continuous flow, outlet or closed cooling, whereas the latter two are more expensive and less efficient, as are dry and hybrid cooling options (Vögele and Markewitz, 2014).

In NRW, 18.3% of the water used in non-public enterprises in Germany is consumed. Of this, 86.9% is consumed for cooling, predominantly (73.7%) in the power generation sector, mostly in conventional power plant operation, followed by use for the production of chemical products (17.3%) (Federal Statistical Office of Germany, 2018).

Thereby, the amount of cooling water in Germany has already been reduced by 30% from 2013 to 2010, due to the energy transition (Federal Statistical Office of Germany, 2016). This also indicates that the links between power generation and waterways are becoming weaker in this regard.

Most German coal-fired power plants are located in NRW and near the Rhine River, which is often used for cooling. However, 60% of the energy generated is discharged into the river as waste heat or dissipated via cooling towers. As this causes the water temperature to rise, the amount of cooling water taken from surface waters is limited, which in turn can lead to cooling water shortages and power plant outages in less resilient SCs. Nevertheless, there are barely any companies claiming water withdrawal from the West German canal network as confirmed by our survey (Section F.4.3).

F.4.3.1.4 Interdependencies

The collected data shows the significance of IWT in NRW for transported goods. On the other hand, the energy transition means that electricity supply is becoming increasingly independent of IWT, because most renewable energy sources require little to no direct water. Only for traditional thermal coal-fired power plants IWT plays an important role, because a large part of coal is transported by waterway: in 2018 about 26 million tons of coal, crude oil and natural gas, which corresponds to about 28.15% of the total transport volumes of coal, crude oil and natural gas (Federal Statistical Office of Germany, 2021a).

In addition, waterways serve as a source of cooling and industrial water, although there are also alternative ways of cooling and the water demand is mostly met by groundwater rather than surface water. This type of interdependence also applies significantly to conventional thermal power plants, whereas most of the water sources do not affect the canal network in NRW rather than rivers like the river Rhine.

The considered interdependencies are illustrated by Figure F.11. For the corresponding sectors we carried out the IOM/IIOM analysis as described in Section F.3.3.

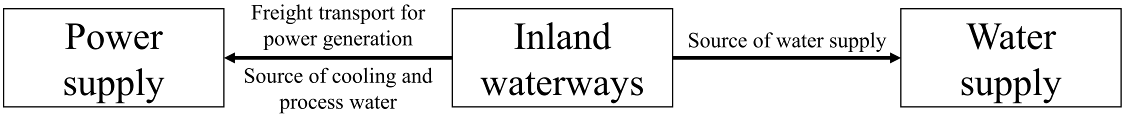

Figure F.11: Interdependencies of IWT and water and power supply

F.4.3.2 Input-Output-Model

F.4.3.2.1 Data and application of IOM

We use the Input-Output Table of 2017 (Revision 2019; Federal Statistical Office of Germany, 2020) to analyze supply-side shocks of IWT towards the sectors of water and energy supply. Figure F.12 shows effect indices and sensitivities of 72 commodity groups in Germany, highlighting the CI relevant groups, which refer to IWT (40), electricity (29) and water supply (31). This reveals that electricity as a key sector can easily drive the development of other sectors, but can also easily be influenced by them simultaneously. Moreover, IWT is located in the fourth quadrant and is therefore a strong backward linkage sector that is not easily influenced by other sectors, but can promptly influence the other sectors. In contrast, the water sector belongs to the

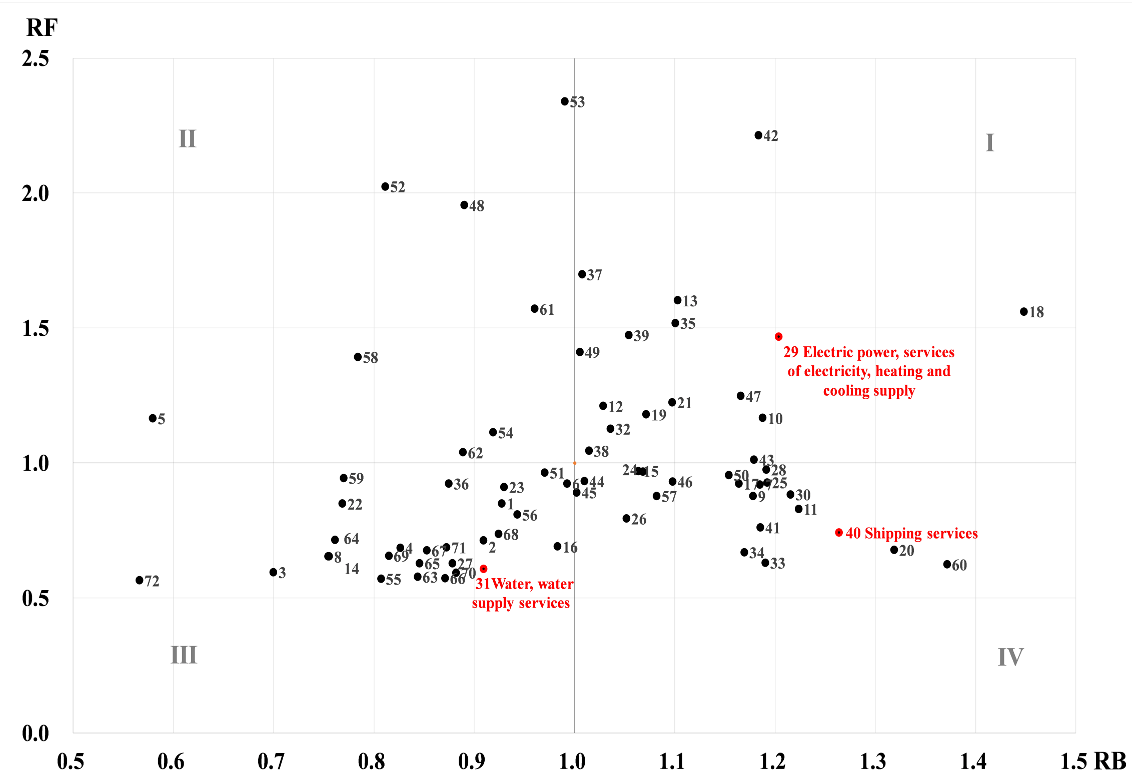

Figure F.12: Backward and forward linkages of sectors
(with effect index RB and sensitivity RF)

weak linkage sectors, which can hardly be influenced by other sectors and can hardly influence the other sectors. This reflects the qualitative classification of the interdependencies of considered CIs in Germany, while more specific results can be obtained by applying the supply-side IIOM.

We consider the supply-shock level, which depicts damage to waterway infrastructure. Two cases are distinguished: (S1) a supply shock of 10% and (S2) consideration of maximum inoperability, i.e., decline in supply by 100%. These disturbances reflect supply shocks stemming from the IWT-domain as a result of a failed transport function caused by the defined scenarios (Section F.4.2.1). Therefore, Exp. F.12 leads to maximal inoperability, if Exp. F.14 applies for commodity group i:

$$z_i^* = \frac{\widetilde{z}_i}{\widehat{x}_i} \qquad \text{(Exp. F.14)}$$

Moreover, the impact of a maximum disruption in the transportation sector on the supply sector is calculated according to Exp. F.14 from the planned supply in the transportation sector (37.719 billion euros) and the planned total production (69.265 billion euros) to a maximum supply shock of 0.5446. Nevertheless, this evaluation neglects IWT's share of the transport sector, which is why results must be put into perspective, as it is done in the following.

F.4.3.2.2 Supply-side IIOM in NRW

The employed IOTs do not sufficiently account for regional differences, which is why we use regional IOTs for the supply-side IIOM that only shows the relationships between 16 sectors (Kronenberg and Többen, 2011). Those include "electricity, gas and water supply" (sector E) and transport, storage and communication (sector I), as shown by Table F.9.

A	Agriculture, hunting, forestry	**E**	**Electricity, gas and water supply**	**I**	**Transport, storage and communication**	M	Education
B	Fishing	F	Construction	J	Financial intermediation	N	Health and social work
C	Mining and quarrying	G	Wholesale and retail trade, repair services	K	Real estate, renting and business support activities	O	Other community, social and personal services
D	Manufacturing	H	Hotels and restaurants	L	Public Administration, compulsory social security	P	Activities of households

Table F.9: Sectors of regional IO-Table
(Kronenberg and Többen, 2011)

To conclude from sector I to IWT, we assume IWT's share of all freight transport services in NRW of 12% (Ministerium für Bauen, Wohnen Stadtentwicklung und Verkehr des Landes Nordrhein-Westfalen, 2016). In addition, we determine the share of canal-based freight transport by IWT of the shipping transport volume in NRW to 60% (Federal Waterways and Shipping Agency of Germany, 2014). Thus, 7.2% of the value added in Sector I is attributable to IWT in NRW.

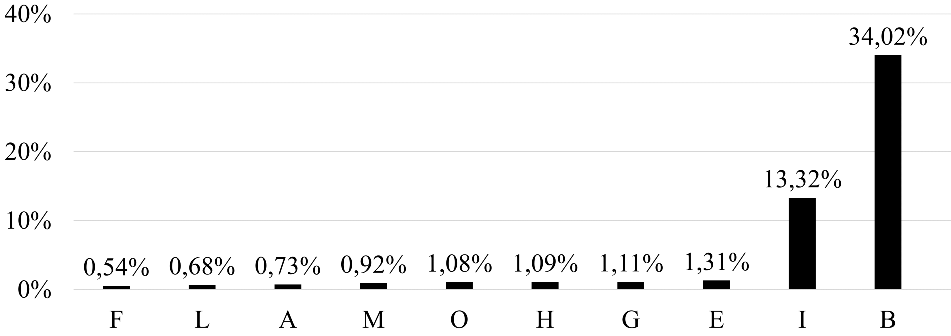

Figure F.13: Impact of 10% inoperability in sector I

To assess possible impacts of a complete failure of the canal network in NRW, we assume that the calculated share is omitted from value creation and assume a spread among affected transport modes and routes as the river Rhine, i.e., summing up to an assumed inoperability of 10%. Figure F.13 reveals the fishing sector (B) as most affected with an inoperability of 34.02%, because it is particularly dependent on the transport sectors. The transport sector (I) exhibits higher inoperability than the initial supply shock due to interdependencies of the sectors, whereas, the "Electricity, gas and water supply" sector has an inoperability of only 1.13%.

Moreover, Table F.10 shows the results when we apply the previously described relationships between freight transport and canal transport in NRW. It can be seen that even if we assume sector E to absorb the total of freight transport, there is only a reduction by 0.51% of sector E, even if we assume a maximum shock of the sector.

	sector I on sector E	**IWT on sector E**	**canals on sector E**
10% supply shock	1.31%	0.16%	0.09%
Max. supply shock	7.15%	0.86%	0.51%

Table F.10: Inoperability of sector E resulting from supply restriction of canals

Concluding, our sub-question (2) (*Are there any conceivable impacts on other CIs, which could result in cascading risks?*) can be answered in our case with no, since the observed impacts are negligible in terms of critical supplies.

F.5 Summary, discussion and conclusions

In this contribution, we carried out a risk assessment of the waterway infrastructure as a barely studied transport system. We analyzed risk exposure stemming from an overaged building stock and had a focal look at interdependent infrastructure as well as the economic effects on potentially affected industries. We integrated the application of input-output modelling in a software-based decision support tool with a high level of usability and decision transparency. The procedure of the presented framework was applied to the case of the West-German canal system.

Apart from its practical value to stakeholders from industry or (regional) government, there is a number of analytical insights, which can be drawn from this empirical framework. First, the close interconnection of the systems under consideration becomes obvious. Second, impacts on industry and population become evident if waterways are not maintained. However, the impact of actual cascading effects caused by critical supply bottlenecks is observed to be comparatively low. The analysis of interrelationships and impacts is therefore primarily of interest for decision makers of infrastructure operators as well as to risk analysts and corresponding research fields.

The results of the IIOM show that a region-wide complete outage of shipping will affect power and water supply, but will not cause significant disruptions. It can also be noted that a supply shock can amplify the initial disruption.

Moreover, our framework provides an applicable setting to incorporate empirical data and expert's knowledge into the development of a risk-based maintenance strategy. Thereby, the vulnerability of construction structures as well as consequences for industry and population can be integrated, taking into account risk preferences of the decision-maker. Thus, decision makers can benefit from our approach and GIS-based application, since a risk-based maintenance strategy is enabled, considering the complex interdependencies among infrastructures.

Further work should include a calibration of our suggested weighting for goal-prioritizing together with the ambiguity preferences as a transparent and usable control lever for the risk assessment. To fully exploit the potential of the provided tool as a risk controlling-device for maintenance strategies, further work should focus on implementing it as a public authority-wide application. This raises the issue of data protection, which is why we recommend to import the data into a spatial database and to realize the data provision via appropriate interfaces and a PHP backend. This offers the particular advantage that data access can be regulated according to special specifications or access rights.

Since the application of the tool to the status quo of the system does not allow editing of the geodata directly via the web browser, changes to the data set must be made directly in the GIS and the files must be exchanged accordingly. Further developments should therefore enable and implement enhanced forms of direct editing in the browser.

Acknowledgments

The authors want to thank the partners in the joint research project for Digital and Transport (2018). The project is funded by the security research program (www.sifo.de) of the German Federal Ministry of Education and Research (BMBF; grant number 13N14697). Special thanks goes to Fabian Neff and Alexander Tolle for supporting the risk dashboard.

References

Akkermann, J., Weiler, S., Bödefeld, J., Marsili, F. (2020). Vulnerabilität von Verkehrswasserbauwerken.

Akkermann, J., Weiler, S., Bödefeld, J., Meier, J. (2018). Die Bauwerksrobustheit im Kontext eines risikobasierten Erhaltungsmanagements. *Beton- und Stahlbetonbau*, *113*(10), 716–726.

Ayyub, B. M. (2014). Systems Resilience for Multihazard Environments: Definition, Metrics, and Valuation for Decision Making. *Risk Analysis: An official Publication of the Society for Risk Analysis*, *34*(2), 340–355.

Balducelli, C., Bologna, S., Di Pietro, A., Vicoli, G. (2005). Analysing Interdependencies of Critical Infrastructures Using Agent Discrete Event Simulation. *International Journal of Emergency Management*, *2*(4), 306.

Barton, D. C., Stamber, K. L. (2000). *An Agent-Based Microsimulation of Critical Infrastructure Systems* (No. SAND2000-0808C). Albuquerque, NM (US).

Beer, T., Ziolkowski, F. (1995). *Environmental Risk Assessment: An Australian Perspective*. Barton, A.C.T., Supervising Scientist.

Buldyrev, S. V., Parshani, R., Paul, G., Stanley, H. E., Havlin, S. (2010). Catastrophic Cascade of Failures in Interdependent Networks. *Nature*, *464*, 1025–1028.

Chenery, H. B., Watanabe, T. (1958). International Comparisons of the Structure of Production. *Econometrica*, *26*(4), 487.

Craighead, C. W., Blackhurst, J., Rungtusanatham, M. J., Handfield, R. B. (2007). The Severity of Supply Chain Disruptions: Design Characteristics and Mitigation Capabilities. *Decision Sciences*, *38*(1), 131–156.

Eusgeld, I., Nan, C., Dietz, S. (2011). "System-of-Systems" Approach for Interdependent Critical Infrastructures. *Reliability Engineering & System Safety*, *96*(6), 679–686.

Farahani, R. Z., Drezner, Z., Asgari, N. (2009). Single Facility Location and Relocation Problem with Time Dependent Weights and Discrete Planning Horizon. *Annals of Operations Research*, *167*(1), 353–368.

Federal Ministry for Digital and Transport (Ed.). (2014). VV-WSV 1102 Objektkatalog: Verwaltungsvorschrift der Wasserstraßen- und Schifffahrtsverwaltung des Bundes.

Federal Ministry for Digital and Transport (Ed.). (2015). Verkehrsinfrastrukturbericht.

Federal Ministry for Digital and Transport (Ed.). (2019). Masterplan Binnenschifffahrt.

Federal Ministry of the Interior and Community (Ed.). (2009). Nationale Strategie zum Schutz kritischer Infrastrukturen: KRITIS-Strategie.

Federal Ministry of the Interior and Community (Ed.). (2011). Schutz Kritischer Infrastrukturen – Risiko- und Krisenmanagement: Leitfaden für Unternehmen und Behörden.

Federal Statistical Office of Germany (Ed.). (2016). *Pressemitteilung Nr. 277 vom 11. August 2016: 2013: Kühlwassereinsatz in der Energieversorgung sinkt um 35 %*. Retrieved 12.01.2022, from http://www.destatis.de/DE/Presse/Pressemitteilungen/2016/08/PD16_277_322.html

Federal Statistical Office of Germany (Ed.). (2017). *Verkehr im Überblick*. Retrieved 28.08.2020, from http://www.destatis.de/DE/Themen/Branchen-Unternehmen/Transport-

Federal Statistical Office of Germany (Ed.). (2018). *Pressemitteilung Nr. 451 vom 21. November 2018*. Retrieved 11.01.2022, from http://www.destatis.de/DE/Presse/Pressemitteilungen/2018/11/PD18_451_322.html

Federal Statistical Office of Germany (Ed.). (2019). Verkehr: Güterverkehrsstatistik der Binnenschifffahrt. , *4*(8).

Federal Statistical Office of Germany (Ed.). (2020). *Volkswirtschaftliche Gesamtrechnungen: Input-Output-Rechnung nach 12 Gütergruppen / Wirtschafts- und Produktionsbereichen: 2017 (Revision 2019, Stand: August 2020)*. Retrieved 12.01.2022, from http://www.destatis.de/DE/Themen/Wirtschaft/Volkswirtschaftliche-Gesamtrechnungen-Inlandsprodukt/Publikationen/Downloads-Input-Output-Rechnung/input-output-12-guetergruppen-pdf-5815117.html

Federal Statistical Office of Germany (Ed.). (2021a). *Beförderungsmengen nach Güterabteilungen und Verkehrsträgern in 1 000 Tonnen für Eisenbahn, Binnenschifffahrt, Seeverkehr und Straßenverkehr inländischer Lastkraftwagen*. Retrieved 07.02.2022, from http://www.destatis.de/DE/Themen/Branchen-Unternehmen/Transport-Verkehr/Gueterverkehr/Tabellen/verkehrstraeger-gueterabteilung-a.html

Federal Statistical Office of Germany (Ed.). (2021b). *Beförderungsmenge und Beförderungsleistung nach Verkehrsträgern*. Retrieved 07.02.2022, from http://www.destatis.de/DE/Themen/Branchen-Unternehmen/Transport-Verkehr/Gueterverkehr/Tabellen/gueterbefoerderung-lr.html

Federal Waterways and Shipping Agency of Germany (Ed.). (2014). *Verkehrsbericht 2013 Niederrhein und westdeutsches Kanalnetz*. Retrieved from http://henry.baw.de/handle/20.500.11970/105054?show=full

Fekete, A. (2011). Common Criteria for the Assessment of Critical Infrastructures. *International Journal of Disaster Risk Science*, *2*(1), 15–24.

Fujimoto, T. (2011). *Supply Chain Competitiveness and Robustness: A Lesson from the 2011 Tohoku Earthquake and Supply Chain "Virtual Dualization"*.

Grogan, P. T., de Weck, O. L. (2018). Infrastructure System Simulation Interoperability Using the High-Level Architecture. *IEEE Systems Journal*, *12*(1), 103–114.

Grubbstrom, R. W., Tang, O. (2000). An Overview of Input-Output Analysis Applied to Production-Inventory Systems. *Economic Systems Research*, *12*(1), 3–25.

Haimes, Y. Y. (1981). Hierarchical Holographic Modeling. *IEEE Transactions on Systems, Man, and Cybernetics*, *11*(9), 606–617.

Haimes, Y. Y., Jiang, P. (2001). Leontief-Based Model of Risk in Complex Interconnected Infrastructures. *Journal of Infrastructure Systems*, *7*(1), 1–12.

Hallegatte, S. (2008). An Adaptive Regional Input-Output Model and its Application to the Assessment of the Economic Cost of Katrina. *Risk analysis : an official publication of the Society for Risk Analysis*, *28*(3), 779–799.

Haraguchi, M., Lall, U. (2015). Flood Risks and Impacts: A Case Study of Thailand's Floods in 2011 and Research Questions for Supply Chain Decision Making. *International Journal of Disaster Risk Reduction*, *14*, 256–272.

Hauptmanns, U., Werner, W., Herttrich, M. (1987). *Technische Risiken: Ermittlung und Beurteilung*. Berlin, Heidelberg and s.l.: Springer Berlin Heidelberg.

Hintjens, J., van Hassel, E., Vanelslander, T., van de Voorde, E. (2020). Port Cooperation and Bundling: A Way to Reduce the External Costs of Hinterland Transport. *Sustainability*, *12*(23), 9983.

Hirschman, A. O. (1958). *The Strategy of Economic Development*. New Haven: Yale University Press.

Hodges, J. L., Lehmann, E. L. (1952). The use of Previous Experience in Reaching Statistical Decisions. *The Annals of Mathematical Statistics*, *23*(3), 396–407.

Huth, M., Romeike, F. (Eds.). (2016). *Risikomanagement in der Logistik: Konzepte - Instrumente - Anwendungsbeispiele* (1st ed.). Wiesbaden: Springer Gabler.

Hüttelmaier, T., Käser, B., Akkermann, J., Weiler, S. (2019). Mehrdimensionale Risiken und Gefährdungen durch Instandsetzungsstau bei Verkehrsinfrastrukturen. *Bevölkerungsschutz*(4), 28–33.

Ivanov, D., Dolgui, A. (2019). Low-Certainty-Need (LCN) Supply Chains: A New Perspective in Managing Disruption Risks and Resilience. *International Journal of Production Research*, *57*(15-16), 5119–5136.

Katina, P. F., Hester, P. T. (2013). Systemic Determination of Infrastructure Criticality. *International Journal of Critical Infrastructures*, *9*(3), 211.

Kronenberg, T., Többen, J. (2011). *Regional Input-Output Modelling in Germany: The Case of North Rhine-Westphalia.*

Kula, M. (2008). *Supply-USE and Input-Output Tables, Backward and Forward Linkages of the Turkish Economy* (No. 16).

Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen (Ed.). (2020). *Erneuerbare Energien.* Retrieved 11.01.2022, from `http://www.lanuv.nrw.de/klima/klimaschutz-in-nrw/erneuerbare-energien`

Lenz, S. (2009). *Vulnerabilität kritischer Infrastrukturen.*

Leontief, W. (1986). *Input-Output Economics*. New York: Oxford University Press.

Lücker, F., Seifert, R. W., Biçer, I. (2019). Roles of Inventory and Reserve Capacity in Mitigating Supply Chain Disruption Risk. *International Journal of Production Research*, *57*(4), 1238–1249.

Mejia-Dorantes, L., Paez, A., Vassallo, J. M. (2012). Transportation Infrastructure Impacts on Firm Location: The Effect of a New Metro Line in the Suburbs of Madrid. *Journal of Transport Geography*, *22*, 236–250.

Ministerium für Bauen, Wohnen Stadtentwicklung und Verkehr des Landes Nordrhein-Westfalen (Ed.). (2016). *Mobilität in Nordrhein-Westfalen Daten und Fakten 2015/2016: Straßenverkehr – ÖPNV und Eisenbahn – Binnenschiffsverkehr – Luftverkehr.* Retrieved 01.12.2022, from http://broschuerenservice.nrw.de/vm/shop/Mobilit%C3%A4t_in_Nordrhein-Westfalen_Daten_und_Fakten_2015_2016

Mitteldeutscher Rundfunk (Ed.). (2021). *Kohlekraftwerke gehen früher vom Netz – woher kommt dann der Strom?* Retrieved 12.01.2021, from http://www.mdr.de/nachrichten/deutschland/wirtschaft/frueherer-kohleausstieg-energie-versorgung-100.html

Novotný, P., Markuci, J., Titko, M., Slivková, S., Řehák, D. (2015). Practical Application Of A Model For Assessing The Criticality Of Railway Infrastructure Elements. *TRANSACTIONS of the VŠB – Technical University of Ostrava, Safety Engineering Series*, *10*(2), 26–32.

Ocampo, L., Masbad, J. G., Noel, V. M., Omega, R. S. (2016). Supply-Side Inoperability Input-Output Model (SIIM) for Risk Analysis in Manufacturing Systems. *Journal of Manufacturing Systems*, *41*, 76–85.

Ouyang, M. (2014). Review on Modeling and Simulation of Interdependent Critical Infrastructure Systems. *Reliability Engineering & System Safety*, *121*, 43–60.

Oztanriseven, F., Nachtmann, H. (2020). Modeling Dynamic Behavior of Navigable Inland Waterways. *Maritime Economics & Logistics*, *22*(2), 173–195.

Park, Y., Hong, P., Roh, J. J. (2013). Supply Chain Lessons from the Catastrophic Natural Disaster in Japan. *Business Horizons*, *56*(1), 75–85.

Rezaei, J., van Roekel, W. S., Tavasszy, L. (2018). Measuring the Relative Importance of the Logistics Performance Index Indicators using Best Worst Method. *Transport Policy*, *68*, 158–169.

Rinaldi, S. M., Peerenboom, J., Kelly, T. K. (2001). Identifying, Understanding, and Analyzing Critical Infrastructure Interdependencies. *IEEE Control Systems*, *21*(6), 11–25.

Rohács, J., Simongáti, G. (2007). The Role of Inland Waterway Navigation in a Sustainable Transport System. *Transport*, *22*(3), 148–153.

Santos, J. R., Haimes, Y. Y. (2004). Modeling the Demand Reduction Input-Output (I-O) Inoperability due to Terrorism of Interconnected Infrastructures. *Risk analysis : an official publication of the Society for Risk Analysis*, *24*(6), 1437–1451.

Temursho, U. (2016). *Backward and Forward Linkages and Key Sectors in the Kazakhstan Economy: Services sector in Kazahstan as an Engine for Diversified Economic Growth - Final Report.* Retrieved 26.01.2022, from http://www.adb.org/projects/documents/kaz-47110-001-dpta-2

Theoharidou, M., Kotzanikolaou, P., Gritzalis, D. (2009). Risk-Based Criticality Analysis. In C. Palmer S. Shenoi (Eds.), *Critical Infrastructure Protection III* (pp. 35–49). Berlin, Heidelberg: Springer Berlin Heidelberg.

Turskis, Z., Zavadskas, E. K., Peldschus, F. (2009). Multi-criteria Optimization System for Decision Making in Construction Design and Management. *Engineering Economics*, *61*(1).

Ukkusuri, S. V., Yushimito, W. F. (2009). A Methodology to Assess the Criticality of Highway Transportation Networks. *Journal of Transportation Security*, *2*(1), 29–46.

Utne, I. B., Hokstad, P., Vatn, J. (2011). A Method for Risk Modeling of Interdependencies in Critical Infrastructures. *Reliability Engineering & System Safety*, *96*(6), 671–678.

Vazsonyi, A. (1954). The Use of Mathematics in Production and Inventory Control. *Management Science*, *1*(1), 70–85.

Vögele, S., Markewitz, P. (2014). *Szenarien zur Wassernachfrage großer thermischer Kraftwerke* (Vol. 09/2014). Forschungszentrum Jülich.

Wehrle, R., Wiens, M., Schultmann, F. (2022). Measuring Systemic and Cascading Risk of Transport Infrastructure based on a Systemic Approach and Input-Output Modelling using the Example of Waterways.

Wehrle, R., Wiens, M., Schultmann, F., Akkermann, J., Bödefeld, J. (2020). Ebenensystem zur Resilienzbewertung kritischer Verkehrsinfrastrukturen am Beispiel der Wasserstraßen. *Bautechnik*, *97*(6), 395–403.

WSA Westdeutsche Kanäle (Ed.). (2022). *Wasserstraßen des WSA*. Retrieved 05.01.2022, from http://www.wsa-westdeutsche-kanaele.wsv.de/Webs/WSA/Westdeutsche-Kanaele/DE/Wasserstrassen/wasserstrassen_node.html

Zhang, P., Peeta, S. (2014). Dynamic and Disequilibrium Analysis of Interdependent Infrastructure Systems. *Transportation Research Part B: Methodological*, *67*, 357–381.

G Evaluation of the potential of infrastructure funds using the case of inland waterways

Abstract[1]

Purpose - The aim of this paper is to investigate the German population's willingness to pay (WTP) for potential infrastructure funds (IFs), in particular for waterways, and the potential benefits that arise from the funds.
Methodology - An online survey is used to analyze the WTP and influencing variables from a nationwide sample of German households. A multivariate regression approach also sheds light on the complex composition of the influencing variables.
Findings - Funds with different designs show different levels of WTP by the population. It is shown that house ownership and the distance of the place of residence to the waterway are of key importance for the WTP in IFs.
Practical implications - Identified social benefits suggest to conclude that government fund initiatives to improve infrastructure financing in Germany can be beneficial. Furthermore, insufficient knowledge about waterways and IFs among the German population should be enhanced and could increase the corresponding WTP.
Originality - The authors examine the WTP and the benefits of potential IFs integrating empirical studies and focus on waterways.

Keywords: Infrastructure Funds, Waterways, Willingness to pay, Empirical

G.1 Introduction

Inland Waterways (IWs) as comparatively environmentally friendly mode of transport is to be attributed more importance and transport volume in the future (Federal Ministry for Digital and Transport, 2016; Fichert, 2017), whereas a poor state of construction assets, a systemic maintenance

[1] This chapter includes the preprint of the article "Evaluation of the potential of infrastructure funds using the case of inland waterways" by Marcus Wiens, Frank Schultmann, and myself (Wehrle, Wiens, and Schultmann, 2022a).

backlog and scarce or misallocated maintenance resources characterize the deteriorating infrastructure (Akkermann et al., 2020; Hossain et al., 2019). This endangers neighboring industries, other critical infrastructure and, moreover, poses a threat to human life and physical well-being, since the settled population can be flooded, e.g. in the case of a bursting dam (Peng and Zhang, 2012).

Despite a lack of awareness about IWs and their importance among the population (Daehre, 2012), there is a strong association with a high hazard potential in events like breaching of a dam, contaminated culverts or bridge pier hit by a ship. Historical examples in Germany include flooding of the Elbe and Danube rivers in 2002, the leakage of canal water during the construction of a new bridge in 2005, the rupture of a pipeline culvert and the associated interruption of the water supply, or a "simple" error in a control system, which led to flooding with property damage of one million euros (Hüttelmaier et al., 2019).

In combination with the before mentioned threats, neglected or misallocated maintenance measures of deteriorating construction assets pose a serious threat to both business locations and to the population (Oztanriseven and Nachtmann, 2020). Hence, these measures must be planned and performed efficiently, facing various regulatory requirements and a complex set of responsibilities due to the different interests and powers of the federal, state and city governments in Germany (Fichert, 2017).

However, the maintenance backlog and increasing transport volumes cause rising maintenance costs, which hence require innovative, alternative financing approaches (Kumari and Kumar Sharma, 2017; Mostafavi et al., 2014). One way to achieve this are public-private partnerships (PPPs), although their success varies in practice (Fichert, 2017). Moreover, citizen participation in funds can reduce the problem of financing (Njoh, 2011), whereas a suitable fund design can enable citizens to better participate in decision-making. A potential oppositional attitude towards corresponding infrastructure projects can thus be reduced.

The willingness to pay (WTP) of citizens and residents, who are directly or indirectly affected in case of failure of the waterway infrastructure, has received little attention in literature and practice so far and will therefore be considered in more detail in this paper. Accordingly, we aim to analyze the WTP of citizens for targeted investments through dedicated infrastructure funds in waterways and examine the potential impacts.

Our paper is structured as follows: The importance and problems of financing infrastructure are examined in more detail below with focus on waterways in order to provide a structured answer to the question of the WTP by citizens or households and possible consequences. Moreover, empirical methods and models of infrastructure financing are examined, from which requirements for a financing system are concluded in order to exploit the merits of different models. The derived financing mechanism and its funds are presented and the data collection and processing is described which is applied to a case study in Germany, before we elaborate on the findings and conclude with a critical discussion.

G.2 Literature Review

G.2.1 Inland Waterway Infrastructure

Infrastructure as a prerequisite for the mobility of goods and people is becoming increasingly important as a result of ongoing globalization, with the quality of the infrastructure also being a long-term factor in determining the production potential of an economy (Bardt et al., 2014; Behrendt and Trojahn, 2013). Transport infrastructure thereby includes the fixed assets of transport routes as physical infrastructure and transport facilities for securing and guiding as well as transshipment stations (Behrendt and Trojahn, 2013; Federal Ministry for Digital and Transport, 2014b).

Inland waterway transport (IWT) as a globally essential mode of transport (Oztanriseven and Nachtmann, 2020; Rohács and Simongáti, 2007) must use existing capacity reserves in the future to shift traffic from road to IWT, since it is a comparatively environmentally friendly mode of transport (Rohács and Simongáti, 2007), cf. Figure G.3. IWT thus represents an elementary component of logistics chains (Tonn et al., 2021), comprising regional water management in the areas of drinking and service water supply, irrigation, power plant utilization and wastewater disposal. Moreover, the infrastructure serves as flood protection for the riparians, as ecological biotope and provides a high recreational value for people (Oztanriseven and Nachtmann, 2020).

Meanwhile, transport infrastructure is exposed to a variety of hazards, such as natural disasters, malicious attacks, and age-related component failure. Therefore, physical protection and resilience of infrastructure take on increased importance (Wehrle et al., 2020; Zio, 2016). However, considering the example of Germany, structures that are system-relevant for the operation of inland navigation are in an increasingly poor condition, characterized by a massive maintenance backlog. This is caused by a long-lasting investment deficit (Federal Ministry for Digital and Transport, 2019) for which predominately government and administration is responsible. This investment deficit of of about€500 million per year for waterways persists, with an additional increase due to inflation, compensation for the accumulated maintenance backlog, and measures not taken into account at the time of calculation (Daehre, 2012).

IWT in Germany covers approximately 230 million tons of goods annually of freight transported on an infrastructure network of 7.300 kilometers length (Figure G.1) and significant but expandable transport volumes, as Figure G.2 shows. Thus, Figures 1-3 exhibit the need and potential for an expansion towards a sustainable transport infrastructure.

Meanwhile, about 50% of the current building inventory of IWs was built before 1950, and another ten percent before 1900, whilst the high age and lack of maintenance measures lead to an overall poor structural condition with about 55% of the facilities were graded insufficient (Grade 4) or adequate (Grade 3), as Figure G.4 shows (Federal Ministry for Digital and Transport, 2015).

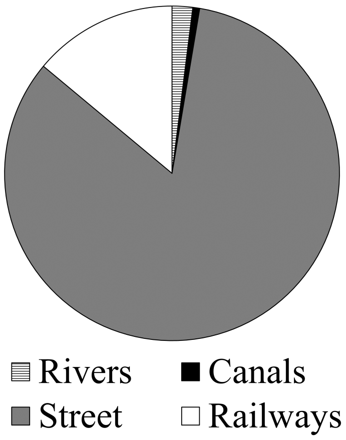

Figure G.1
Length of transportation infrastructure in Germany in the year 2020
(Federal Statistical Office of Germany, 2022)

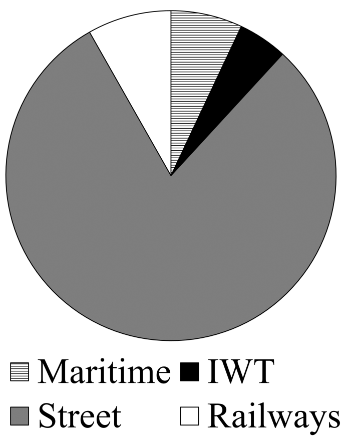

Figure G.2
Transport volumes by mode in the year 2020
(Federal Statistical Office of Germany, 2020)

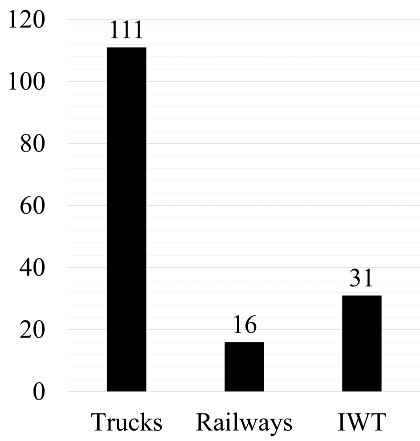

Figure G.3
Emissions in freight transport in CO2 equivalents
(Federal Environment Agency of Germany UBA, 2021)

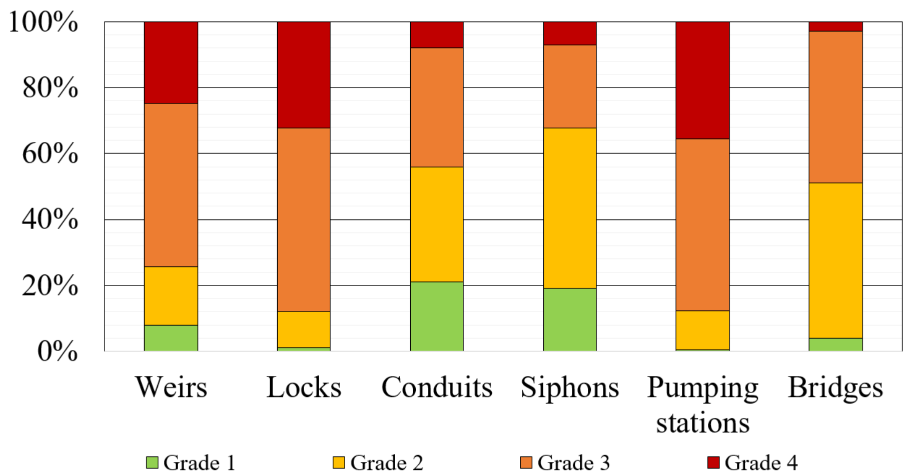

Figure G.4: Condition assessment of building structures in Germany
(Federal Ministry for Digital and Transport, 2015; Hüttelmaier et al., 2019)

Increasing deterioration and a lack of maintenance measures result in structurally more vulnerable infrastructures (Houlihan, 1994; Lenz, 2009; Wehrle et al., 2020). Accordingly, not least external factors, such as natural events, human error or terrorist attacks, are likely to lead to the failure of facilities as a result of their poor condition, and consequently to high economic losses and the endangering of human lives (Hüttelmaier et al., 2019; Tonn et al., 2021).

At the same time, infrastructure investment in relation to the development of GDP is experiencing a significant decline, leading to a progressive depletion of assets due to underfunding (Bardt et al., 2014; Behrendt and Trojahn, 2013; Daehre, 2012).

Demographic developments, globalization, climate protection, environmental compatibility and the scarcity of fossil resources will also shape the demands on the transport infrastructure in the future (Daehre, 2012). Thus, transport infrastructure, which has long been acknowledged as Germany's locational advantage, threatens to become a disadvantage in the future (Bardt et al., 2014). The inadequate and deteriorating condition already results in annual economic costs in the range of several billion euros due to lost time, environmental pollution and higher operating costs (Kopper et al., 2013).

G.2.2 Stakeholder

The complexity of infrastructure planning increases due to the different responsibilities and interests of various stakeholders, which, along with the level of concern, can change over time, with interests being diverse and even conflicting (Fichert, 2017; Francis and Bekera, 2014). Stakeholders of waterways are identified in the following.

G.2.2.1 State/Government

Tasks of the state include duties of services of general interest (Große Hüttmann and Wehling, 2013) as well as the responsibility for planning, construction and operation of infrastructure of the public sector as the developer, while developers can be the federal government, the state or the municipality (Daehre, 2012). The public sector has sovereignty over policies and legislation on planning and construction and is responsible for taxes and fees to provide modes of transportation. The fundamental interests of the responsible parties lie in a low risk of failure in order to keep failure costs low and not to jeopardize the reputation of their own organization (Tonn et al., 2021), which corresponds to the preservation of electoral votes.

The interests of the government's roles can be conflicting, as it acts as a project promoter on the one hand while seeking to preserve other public interests such as environmental protection and safety. The state must take particular care to ensure that its actions have a signal effect: If the government pays for damage caused by infrastructure failure, there is no incentive for potentially affected parties, citizens or companies, to insure themselves in advance or to invest in measures to repair the infrastructure (Tonn et al., 2021).

G.2.2.2 Population

By tax levies, the population is the main financier of waterways, with 90% of residences not being at risk of flooding and thus expected to be less affected and interested in the reliability of hydraulic engineering facilities (GDV, 2021). General interests include the avoidance of flooding and of indirect ripple effects causing shortages of supply (e.g., in the supply of power plants in the region), but also the avoidance of citizen-supported user financing such as a passenger car toll (Statista, 2013). This is to be expected in the case of waterways in particular, since the willingness to pay for a previously seemingly free service is low and can cause resentment, political resistance and the loss of votes (Kopper et al., 2013). In addition, employees such as about 4,400 IW skippers (Statista, 2021) and other indirectly dependent jobs in logistics, electricity and water supply or passenger transport have special interests.

Infrastructure projects require the consideration of public perception, since involvement and communication with communities require the increased investment of sufficient time and resources to reduce oppositional attitudes among the population (Geekiyanage et al., 2020; Mostafavi et al., 2014). Sufficient information exchange prevents project extensions due to plans that need to be revised (Moss, 2011). Effective participation of local communities and residents must be enabled through planned and moderated participation to avoid chaotic ratios (Geekiyanage et al., 2020; Njoh, 2011; Zio, 2016).

Although waterways provide the risk of flooding, the population is usually uninformed about flood damage and available insurance measures, which is reflected in underinsurance (Osberghaus, 2015). Furthermore, insurance is not available everywhere in the event of a flood or is so expensive that it is not purchased, contrary to the existing interest, which is particularly the case in endangered areas (Bubeck et al., 2013; Osberghaus, 2015). Public perception is also generally critical to the success of new infrastructure financing methods, especially since public support for infrastructure financing responds inelastically to economic factors, but in contrast responds strongly to infrastructure-related factors: If there is an awareness among the population that infrastructure is in need of high maintenance or that its protective function is no longer guaranteed, there is a higher WTP (Mostafavi et al., 2014).

G.2.2.3 Industry

At 6.36 billion euros, shipping on German waterways and rivers accounted for about 0.22% of gross value added in 2017 (Federal Ministry for Digital and Transport, 2021), although indirectly affected sectors must also be taken into account here. The four largest groups, each accounting for over ten percent of the total, in ascending order, are “coal, crude oil and natural gas”, “chemical and mineral products”, “coke and petroleum products”, and “ores, stone and wood products” (Federal Ministry for Digital and Transport, 2021). Expectations and requirements of the industry concern functionality and capacities of IWs.

Besides stakeholders of industry affected by logistics, we have to consider parties involved in planning and construction, since infrastructure planning is conducted in government agencies, offices, and private companies. Consulting agencies, engineering firms and other intermediary organizations also have an influence on planning (Moss, 2011).

G.2.2.4 Investors and others

Private companies are one of the most important stakeholders when awarding projects under PPPs, but there are currently no PPPs in the shipping industry. The goal of private capital investors is to generate profits on their investments (Mishra et al., 2013), which is why infrastructure investments without profit prospects are unattractive to private capital investors. One incentive for investing in infrastructure is lower volatility, portfolio diversification, and inflation mitigation (Gemson and Annamalai, 2015).

Other entities, for example in the form of NGOs but also other states or communities such as the EU, can be regarded as stakeholders.

G.2.3 Function and deficits of funding of waterways

The need for infrastructure investment in expansion and maintenance continues to rise due to increasing demand and use, with infrastructure projects requiring high levels of investment (Houlihan, 1994; Kopper et al., 2013). Since infrastructure is usually provided by the government, also the financing of German waterways is provided almost exclusively from public budgets with annual actual federal budget allocation of€1,000 million, which has historically been cut by half (Federal Ministry of Finance of Germany, 2021) and which is subject to the principles of annularity, non-affection as well as specialty. Previously existing travel levies for partial user financing led to a situation where even the actual cash cow Kiel Canal (Nord-Ostsee-Kanal) exhibited a cost recovery of only 30% (Heitmann et al., 2013).This mechanism has been largely abandoned (Federal Ministry for Digital and Transport, 2019), while concepts of tolls and track access charges are well established in other modes of transport (Daehre, 2012).

Transport economists and representatives from industry complain about too little investment in infrastructure and in some cases call for a fundamental revision of the financing mechanism in Germany (Fichert, 2017). Yet investing in infrastructure is one of the best ways to create economic growth and jobs (Kumari and Kumar Sharma, 2017; Sturm et al., 1999). The enormous discrepancy between the allocated funds and the needs prompted the development of a new concept for investment policy. However, most of the proposals to date have been critically evaluated by stakeholders and countries (Daehre, 2012; Kapesa et al., 2021; Mostafavi et al., 2014).

Even the (re-)introduction of broad-based *navigation levies* would not cover the costs of the infrastructure, especially since the Rhine, potentially the largest source of revenue, is exempted from levies by international treaties (Kopper et al., 2013). Even if all direct users and beneficiaries of waterways, for example power plants, the leisure industry or flood-protected communities, are included in the financing, full cost recovery is unrealistic (Daehre, 2012; Heitmann et al., 2013).

Meanwhile, the possibility of (co-)financing via the private sector is justified in a legitimate economic interest in high quality and density infrastructure, whereas the large sums of investment combined with long construction and payback periods leads to risk-averse behavior (Gemson and Annamalai, 2015). Beyond this, since the security of the population is one of the most important responsibilities of the state, the involvement of private sector partners in critical infrastructure is traditionally challenging (Dunn-Cavelty and Suter, 2009) but nevertheless common for infrastructure operation, whereas holding companies would allow the financing of large projects under the distribution of financial risks (Gemson et al., 2012; Mishra et al., 2013).

Public-private partnerships (PPP) as long-term, contractually regulated collaborations between parties from the private and public sectors to reach better performance and efficiency, cost savings and potential innovations that are unattainable by individual stakeholders (Fandel et al., 2012) are receiving increasing visibility and attention in the literature (Chou and Pramudawardhani, 2015). While public perception is also a success factor for PPPs (Cui et al., 2018), risks include the possible concealment of debts incurred, higher financing costs since the government can borrow money on more favorable terms than the private sector, lack of transparency, venality, a failure to deliver benefits, or distortion of political priorities (Eurodad, 2020). PPPs can also provoke the free-rider problem in which individual participants invest only the minimum necessary in the collaboration in order to maximize their individual benefit from it (Falkinger et al., 2000; Givens and Busch, 2013; Rand and Nowak, 2013).

A *value-added tax* would take into account that investments in infrastructure gradually lift local land prices, granting the receipt of funds by invoking an objective unit of measurement (Coleman and Grimes, 2010). However, only discontinuous payments are received here, which cannot make a decisive contribution to infrastructure financing in realistic amounts.

Another possibility is the potential earmarking of parts of tax revenues, which is input-oriented and thus does not do justice to changes in financial needs, i.e. the required output. Fund structures, for example via performance and financing agreements, allow to combine user and tax funding and enable a better allocation to specific purposes while accompanying periodic reports on the condition. They allow better monitoring and better coordination and planning over the year, which eventually result in higher savings in total (Daehre, 2012; Kopper et al., 2013). This can be oriented towards bond funds, which derive their attractiveness from long periods of stable, low-risk cash flows, while the physical, economic and financial characteristics of investments in the transport sector make them especially suitable for investors (Panayiotou and Medda, 2014).

In general, fund-based models and thus citizen participation, in terms of shares and co-determination rights, can allow more investments according to individual needs (Yildiz, 2014). In this context, it is reasonable for infrastructure managers to issue bonds to reduce capital costs and at the same time to increase the acceptance of infrastructure projects (Beckers et al., 2014). For citizens, investing in infrastructure bonds can make sense at a market rate of return to risk ratio (Yildiz, 2014), while from an aggregated perspective, centralized issuance of citizen infrastructure bonds can reduce transaction costs and bond risks (Beckers et al., 2014). Other manifestations include mezzanine financing, such as savings bonds or corporate bonds, financial vehicles in which citizens only participate financially, without voting rights or liability obligations, and cooperatives, which also allow stakeholders such as small businesses to participate (Yildiz, 2014).

G.2.4 Deficits of alongside mechanisms

While more money for transport infrastructure is a necessary but not sufficient condition, additional reforms of financing, planning and administrative structures are needed (Bardt et al., 2014). Moreover, a larger budget for transport infrastructure may cause debts or cutbacks in other departments (Daehre, 2012).

Although, the German financing system itself contributes to the problem through inefficiencies and misaligned incentives, since financing of infrastructure in Germany exhibits the following shortcomings (Houlihan, 1994; Klockow and Hofer, 1991; Kopper et al., 2013; Moss, 2011; Wehrle et al., 2020):

- High investment requirements for individual projects
- Lack of attractiveness for investments from the private sector
- Financing system characteristics (i.e. annuality) lead to planning delays and uncertainty about future budget
- Lack of attractiveness of maintenance; prioritization of lighthouse-projects
- Lack of planning for maintenance reserves
- Competition with other governmental departments with limited budget
- Lack of qualified personnel and learning processes
- Complexity in planning (lifespan, large number of interfaces)
- Approval procedures; often multiple and long-winded
- Ineffective and inconsistent responsibilities (federal, state)
- Conflict of political interests: short-term election results vs. long-term benefits from infrastructure

Derived from this, target points and levers for more efficient infrastructure financing are illustrated by Figure G.5. Thus, regarding the component of bureaucracy, the state should commit to strengthening capacities to ensure the effective deployment of fund resources (OECD, 2020).

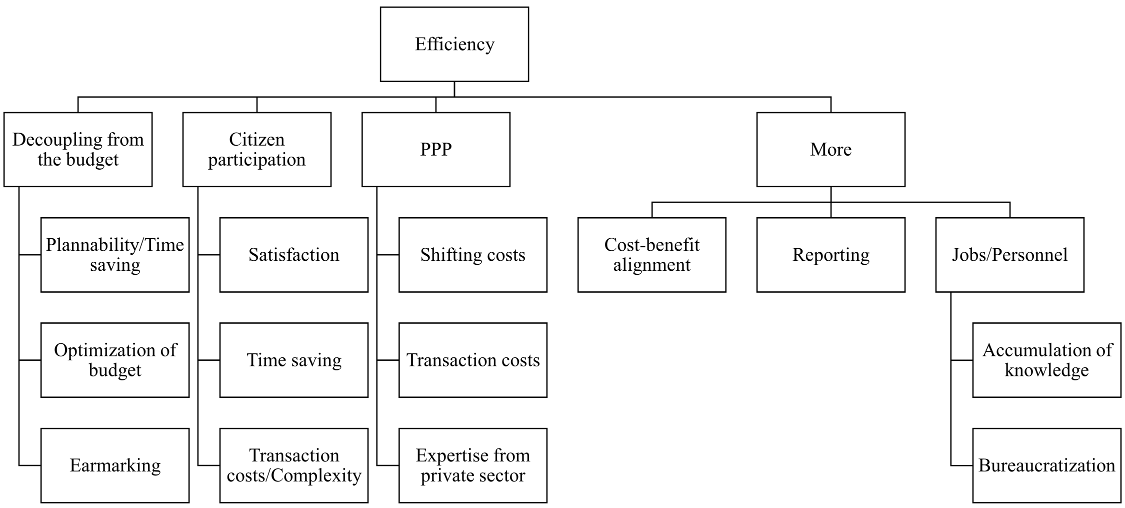

Figure G.5: Factors for a more efficient infrastructure financing

To conclude, we encounter a conceivably unfavorable combination of high hazard potential, low public interest and complete dependence on the public budget which provides an underfunded and inadequate financing system. Simplified, this leads to problems in the form of staff and employment shortages and a lack of maintenance of the existing infrastructure. Consequently, existing substance is being depleted and the associated risk of failure of individual parts of waterways increases, resulting in a threat of economic losses and damages in the future, which in the long term affects the logistical attractiveness of the waterways, resulting in welfare losses and, in extreme cases, could even endanger human lives.

G.2.5 Infrastructure Funds

Infrastructure funds became a recognized alternative investment opportunity during the early 2000s, with stable returns and good diversification for investors (Panayiotou and Medda, 2014). Implementable in the medium term, they can ensure reliable funding for transport infrastructure (Kopper et al., 2013), while decoupling them from annual budget planning and avoiding the influence of political agendas suggests that financial resources can be allocated in an economically sensible way, which can lead to an improvement of conditions of transport infrastructure. Moreover, an exemplary fund for flood protection is established in france with the Barnier fund which is “almost self-sustainable” (OECD, 2020), showing the possible efficiency of a damage reduction component.

Private infrastructure funds first raise money from investors while a fund manager analyzes, evaluates, selects and then invests in existing investment opportunities in infrastructure projects (Bitsch et al., 2010; PwC, 2016). In addition to the fund, it is necessary to introduce a financing company for the various modes of transport and management of the fund, including the possibility of expanding PPP models (Daehre, 2012). As a result, the fund manager’s expertise is utilized in the selection of investment projects, while at the same time enabling broad investment and diversification in various areas of infrastructure (Kleine et al., 2015), Panayiotou and Medda (2014) report potential yields of 15-20%.

Thus, stable returns with low risk are expected (Bianchi et al., 2014; Cohen and Kamga, 2013). Other benefits include directly available capital and better management, as well as the potential for faster, cheaper, and better project execution (Gemson and Annamalai, 2015). In this regard, long-term relationships between the private capital investor and investment recipient are beneficial (Morasch and Tóth, 2008).

The use of infrastructure funds has the following overall objectives (Daehre, 2012):

- Internalization of external costs and infrastructure costs
- Sustainable securing of financial requirements by earmarking funds (covering actual needs)
- Transparency regarding the use of funds
- Decoupling from the annual budget and thus stabilization of the financing process (independence from influences on the budget)
- Implementation of measures based on cost-benefit analyses and economic efficiency

- Optimal use of available funds from public and private sources

The type and structure of infrastructure funds can vary, with (S1) the timing of the investment, (S2) the type of infrastructure financing, and (S3) the investment instruments as relevant characteristics, according to PwC (2016):

(1) Timing: Investments can be made in construction phases (greenfield investment), associated with higher investment sums, risks and returns, or in operational phases (brownfield investment; i.e. maintenance of waterways).
(2) Type: Tax-financed infrastructure operation is more attractive from the fund's point of view due to the lower risk compared to user financing and is to be planned for in the contract design so that the government does not bear the entire project risk.
(3) Instruments: Equity as investment source can be realized by the emission of shares (or bonds in the case of debt capital) and usually offers a higher return. Alternatively, loan funds invest directly in projects by issuing loans.

Prerequisites ideally include sufficient availability, satisfactory regulatory underpinnings as well as funding mechanisms and aligned interests of fund managers and investors. In addition, it is important that investments spread geographically and across different infrastructures to be attractive and avoid idiosyncratic risks (Panayiotou and Medda, 2014), whereas the state must prevent the exploitation of infrastructure facilities by equity investors (Baird, 2013; Moles and Williams, 1995)).

The cost-benefit analysis of the fund within the scope of the funds design must consider that reduced costs through increased acceptance are expressed in faster completion and fewer legal costs, whereby the costs incurred through returns on the bonds and transaction costs of the bonds must be set against each other, provided that the citizen participation is based on financial stakes and not other forms of attachment (Beckers et al., 2014). It can also be taken into account that citizens have a higher willingness to contribute financially to projects when local authorities lack financial resources (Zhang, 2014).

Factors influencing WTP are mainly the administration and use of financial resources, while the peer effect influences the acceptance of financing methods in that a new fund model with similar structures to already established funds (peers) leads to higher acceptance (Mostafavi et al., 2014). Alternatively, it is conceivable to create a "proof of concept" with lighthouse projects and thus increase acceptance.

Due to the peer effect (Mostafavi et al., 2014; Zhang, 2014), major deviations from the norm should be made in gradual steps for new funds and financing methods. Appropriate communication about investment needs must also take place to make citizens aware of the existing problem (Zhang, 2014). Disadvantages particularly concern the state's perspective and, depending on the fund's design, involve a possible shortfall in the predictability of funding in the case of phased financing (Gemson and Annamalai, 2015) as well as the problem of "obsolescing bargaining," which describes the shifted bargaining powers before and after the construction of infrastructure (Post and Murillo, 2016; Ramamurti, 2003).

The suitability of a fund thus depends on various characteristics as well as the contractual arrangement, while a departure from or supplement to the current type of infrastructure financing and provision seems sensible. The literature tends to focus on the participation of the private sector rather than on financing through organized citizen participation which is the approach of this paper.

G.2.6 Willingness to Pay for transport infrastructure as public good

G.2.6.1 Concept

Goods can be divided into four groups based on the criteria of excludability (excluding persons or groups from the consumption and use of the good) and rivalry (the consumption of the good by one user hinders or prevents the consumption of another) (Helfrich, 2014). Thus, since the broader population is less likely to use waterways directly than to derive indirect benefits from them, and since excludability, such as through conservation zones, is assumed to be negligible, waterways with their construction facilities are considered a public good, waterways can be seen as public good.

The efficient provision of a public good requires that the marginal cost of providing the good equals the sum of the marginal benefits, i.e. the sum of the consumers' marginal rates of substitution (marginal WTP) must equal the marginal rate of transformation for the public good (marginal cost) (Samuelson, 1954). Hence, the cumulated WTP must equal the actual expenditures (transformation). This condition does not require equal distribution of costs or WTPs into a fund, i.e., factors such as distance from home to waterway may influence different marginal WTP for individuals.

G.2.6.2 Related studies

Studies on the WTP of fund-based citizen participation in infrastructure financing barely exist. Among those relevant for our elaborations we find Spegel (2017) identifying a marginal WTP of 30 cents for flood damage prevention to property real estate in the Swedish population, with water supply security experiencing the highest WTP as opposed to road disruption prevention.

The investigation that is closest to our goal of empirical WTP assessment is provided by Entorf and Jensen (2020) who analyze the WTP for investments in security-related measures by public institutions, especially against floods. The contingent valuation method is used to determine the price of security as a non-tradable good based on a nationwide survey, finding an average WTP of approximately€90, or a median of€50, respectively; Moreover, Entorf and Jensen (2020) conclude that government initiatives to protect against flood risks can be successful, while enhanced risk awareness has a critical impact on WTP.

G.3 Research Methodology

G.3.1 Requirements for the financing mechanism

Infrastructure funds to be considered should achieve an improvement to the current situation of the German waterways, serve the objectives of fund financing as well as advantages of citizen participation. To this end, possible funding of waterways through voluntary contributions from households is considered further, refraining from cross-funding other modes of transportation. Various fund models that address different problems in existing financing are considered to address a lack of capital (Section G.2.3) as well as other structural problems in infrastructure construction (Section G.2.4).

Requirements and assumptions for the funds, moreover, comprise the following:

- Avoidance of the state's indebtedness or rivalry with other departments, which is why citizens and households can pay into the fund on a voluntary basis.
- It is assumed that the state acts as the initiator of the introduction of the funds and can therefore decide on the fund introduced.
- A reporting system for tracking earmarking, transparency and better assessment of financing needs is further assumed to be in place for all potential funds.
- Further potential exists in an internationally standardized reporting system, increased use of PPPs, the creation of positions for better planning and involvement of the population, and central data processing for more targeted prioritization of rehabilitation measures (Tonn et al., 2021).

Analogous to Entorf and Jensen (2020), the WTP of the population for public investment in protective measures to reduce flood damage should be identified and, in addition, the WTP for public investment in the general improvement of the condition of the waterways should be identified by means of a fund.

The benefits for which households should state their WTP are divided into the two major components reduction of opportunity costs, e.g., the avoided costs of flooding by maintaining a dam, and the envisaged increase in the efficiency of the current government system. Figure G.6 serves to illustrate the two components, as well as the directions of impact.

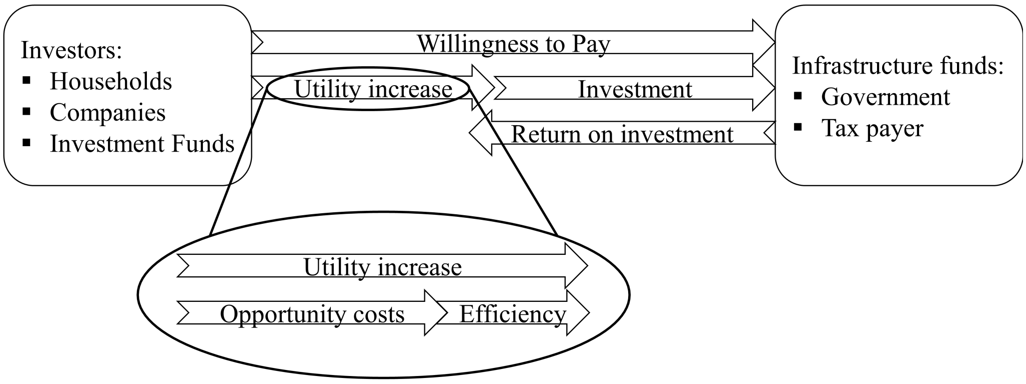

Figure G.6: Context of Willingness to Pay, Utility increase and Investment

G.3.2 Funds Mechanism

G.3.2.1 Framework

The state entails design freedom over the type of fund to be introduced. Figure G.7 shows the decision framework of fund financing as a 2-stage decision process, with the government deciding whether to introduce a fund in the first stage. At the second stage, households each decide individually on their WTPs into funds or private coverage (PC). Each unit of money invested is intended to provide benefits, while the state does not reduce the previous, regular expenditures and investments regarding IWs. PC of households in the following refers to PC against floods and inundation, whereas the specific form (e.g. insurance, reserves or other) as well as legal aspects are not specified here.

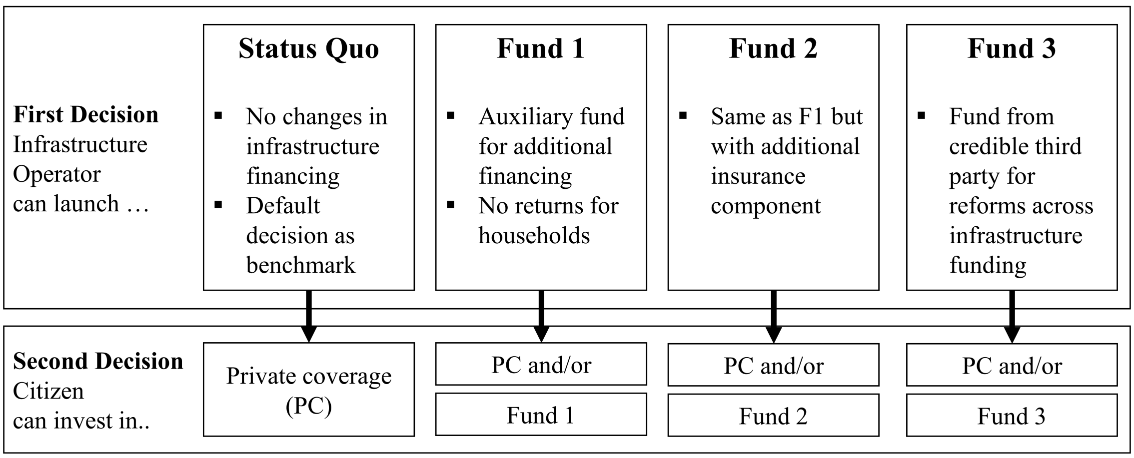

Figure G.7: Decision Framework

As depicted by Figure G.7, we consider three types of funds leading to the four options for the state:

(0) *no fund, i.e., maintaining the status quo*: This default decision by the government means that no changes are made in infrastructure financing, so the only option for households here is PC. The status quo provides a real-world benchmark, i.e., households' WTP for PC is intended to represent an initial measurement without the influence of funds, government, or other depositors and is a replication of the survey from Entorf and Jensen (2020). The state's payout for this scenario is considered as benchmark for evaluating the fund alternatives. The valuation from the state's perspective for the status quo is set equal to zero, as a comparison for positive and negative deviations, respectively, from a guaranteed achievable outcome.

(1) *introduction of fund 1 (F1)*: auxiliary fund for additional financing of IW infrastructure, whereby households should not expect any returns and therefore no disbursement is required. The benefit of the fund is generated by the effects of the implemented measures. The fund is financed by annual contributions. The earmarking relates to expansion, maintenance, optimization of the state's allocation of resources and counteracting a shortage of personnel. For this scenario, the WTP is queried for both investments in F1 and PC.

(2) *introduction of fund 2 (F2)*: F2 generally shares the same characteristics as F1, with F2 including an additional insurance component in the event of floods and inundations, which covers the costs incurred by depositors in the event of a loss. The insurance component could compensate for parts of the underinsurance (Section G.2.2.2) and reduce the dilemma of public goods with the inclusion of insurance, which is exclusive, since in this case it is no longer a purely public good. To this end, a household's utility is extended by a possible insurance coverage, while benefits from the insurance coverage are attributed only to persons who paid in F2.

(3) *introduction of fund 3 (F3)*: resources of F3 are to be spent on reforming the financing of all infrastructure funding to address structural problems, adopting and communicating the following goals by a credible third party as fund provider:

   (a) funding independent of annual budget decisions.

   (b) more positions and staff; and

   (c) enhancing opportunities for community participation.

   The key difference from F1 and F2 is the scope of the fund, as F3 is for the reformation of all modes of transportation (road, rail, etc.), while the other funds are limited to waterways. F3 also seeks to fundamentally change funding directly, so it represents a break with current structures.

G.3.2.2 Survey design

The aspired data regarding the WTP of households for the funds is determined via an online survey, based on the basics of survey design, referring e.g. to replicability, structure, comprehensibility, topic orientation, answerability, sensitivity, social desirability, fatigue factors and influenceability (Brancato et al., 2006).

The final survey includes 54 questions and can be divided into five parts. It takes about 10 to 15 minutes to complete, and the questions are answered anonymously. Figure G.7 provides an overview of the structure of the questionnaire, which can be found in the appendix.

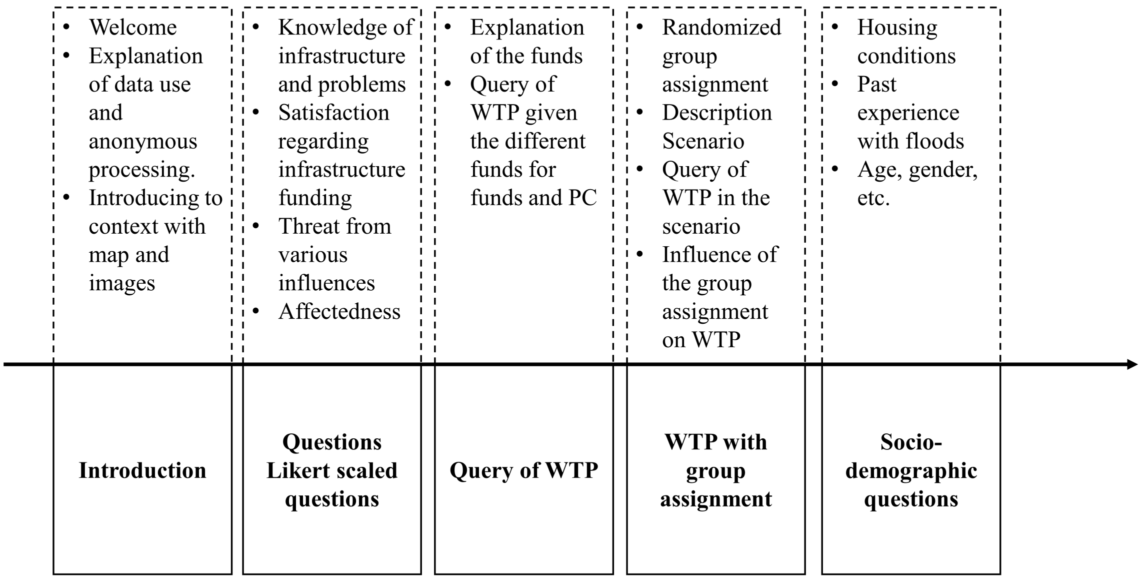

Figure G.8: Structure of the questionnaire

The introduction includes a selection of images showing examples of waterway components and use. The subsequent Likert scales are 7-point from 0 to 6 to derive independent explanatory variables for the WTP. In addition, the general level of knowledge about water-related risks and risk perception of the population are determined. Risk perception is moreover connected to the affectedness of the population such as dependencies via risk of flooding or economical interconnection between the respondent and IWs.

Next, the relevance, deteriorating condition, and funding gap of waterways are mentioned before querying the WTP in scenarios 0-3, where the respondents could freely enter a number in euros.

Survey participants are then randomly assigned to one of four groups from Table G.1 and answer the questions regarding WTP again, with participants now asked to answer the questions from the perspective of their assigned group, omitting F3. The four groups were chosen to measure the influence of housing location and employer concern, as it is suspected that these factors have a high influence on the WTP. The numbering in the matrix corresponds to the numbering in the questionnaire as well as in the data set.

Subsequently, influencing factors of WTP are queried and Likert scale questions are asked again to test for any changes in respondents' perceptions or assessments over the course of the survey, since respondents were expected to now have acquired knowledge and awareness about waterways and

		Housing – distance to the nearest IW	
		Short	70 km
Employer	High dependence on IWs	Group 1	Group 3
	Independent of IWs	Group 4	Group 2

Table G.1: Grouping matrix

their and other potential situations, influencing the respective answers. The survey concludes with sociodemographic questions, including age, gender, income, and household size.

G.3.2.3 Assumptions about Actors' Actions and Fund Outcomes

Based on the considerations from game theory and the characteristics of funds, hypotheses are made regarding fund financing. These are listed by Table G.2.

Hypothesis	Fund	Formulation	Basis
H1	F1	Modal value of WTP for F1 is 0€.	Rationality assumption of households; WTP for F1 low
H2	F1	(Median of) WTP for F1 is around 50€.	Comparable studies show unexpectedly high WTPs of about 50€, cf. Section G.2.6
H3	F2	WTP for F2 is marginally higher than WTP for F1	Exploitation of insurance component, since insurance coverage is available at marginal cost: the insurance component does not discriminate by deposit amount, but only nominally whether a payment is made
H4	F2	WTP for F2 is equal to sum of F1 and PC at F1	F2 takes over the two functions of F1 + PC
H5	F2	WTP for PC at F2 is close to 0€	PC is already covered by F2
H6	all	Home ownership has a significant impact on WTP	Flood damage affects property/assets
H7	all	Doubts about the WTP of others have a high ranking (large influence)	Free-rider problem (Section G.2.3)
H8	all	Likert questions show significant differences in repeated measurement	Acquired knowledge and situation awareness

Table G.2: Hypotheses

G.4 Case

G.4.1 Survey

The survey was conducted from early April 2021 to mid-June 2021, without an exclusive group of participants, and resulted in 113 fully completed questionnaires. The average age was 40.84 years, while the gender distribution (male/female/diverse) was as follows (50.4%/45.1%/4.4%). Similar data for Germany comprises an average age of 44.5 years (Statista, 2022) and a gender distribution of (50.7%/49.3%/0.0%) (Federal Agency for Civic Education of Germany, 2022).

According to Entorf and Jensen (2020), logarithmizing of WTP data was conducted as follows: all WTP were increased by the value 1 before taking the logarithm in order not to lose data of the value 0 and to encounter the possibility of negative WTP's due to the right skewness of the data.

G.4.2 Results

G.4.2.1 Descriptive data

WTPs show high standard deviations according to Figure G.9 while the mode for all specifications corresponds to a WTP of 0€. Also, the median for private coverage, for the status quo, in the case of F1 or F2, is 0. This illustrates the right skewness of the data.

The median value for F1 corresponds to 29.19€ and is significantly lower than that for F2 (45.08€) and higher than that for F3 (18.08€). F3 has the lowest mean value, but at the same time the lowest standard deviation, indicating a more reliable estimation value.

Figure G.10 illustrates the WTP broken down by group (Table G.1), with Group 1 having 40 of the 113 participants randomly assigned. Group 2 (3, 4) have 26 (27, 20) participants. Boxplots of WTP, grouped by assigned group, for funds and private coverage show discernible differences between groups.

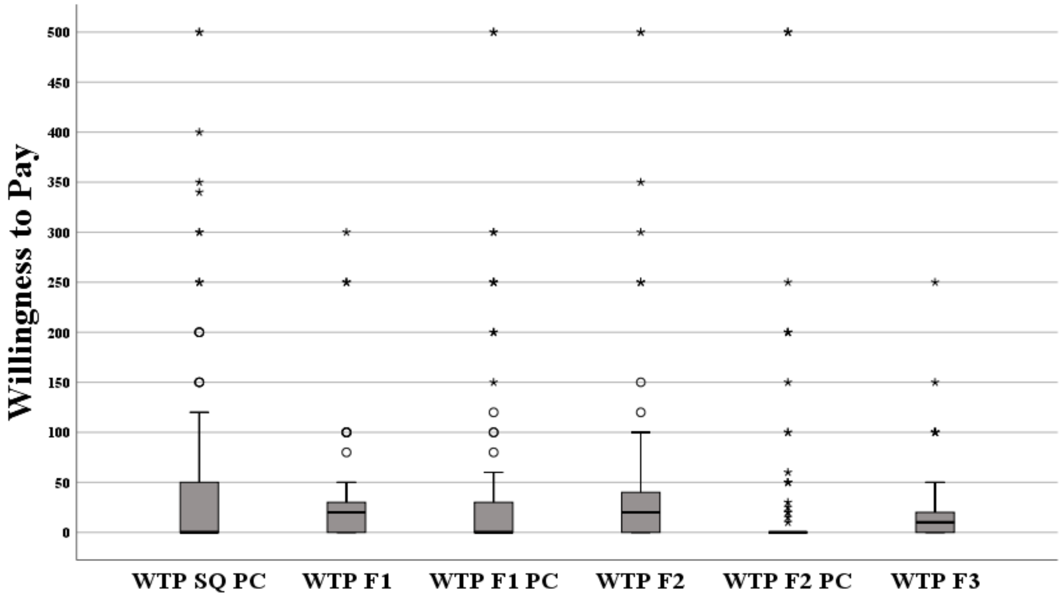

Figure G.9: Willingness to Pay into funds and private Coverage (PC)

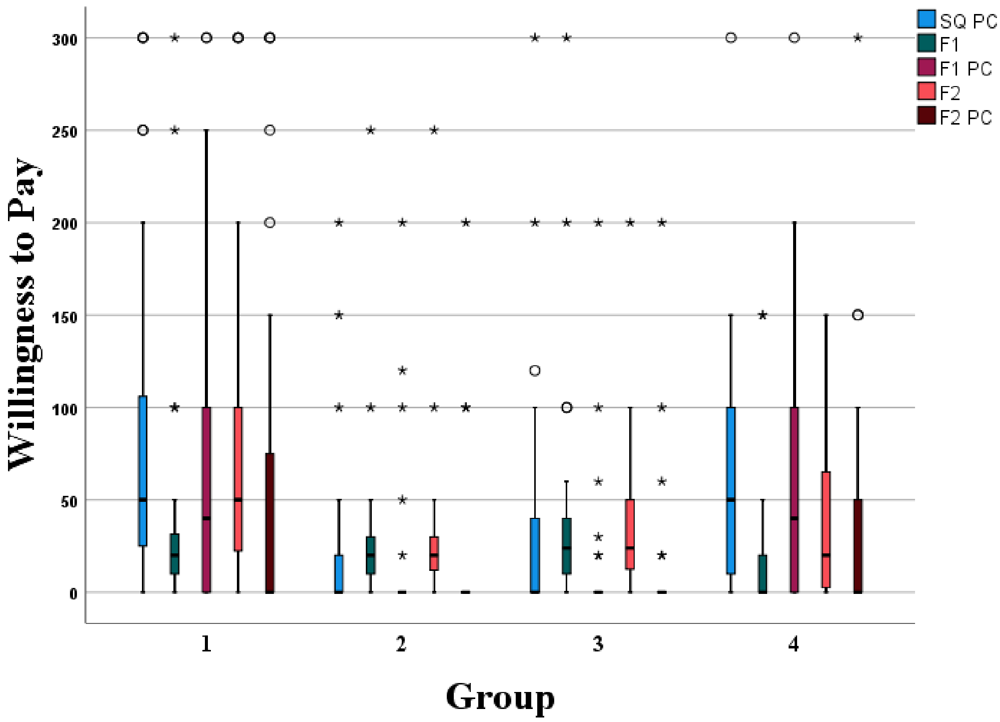

Figure G.10: Willingness to Pay broken down by groups
(14 Data points not displayed with WTP >499)

Within the scope of the ANOVA with repeated measures, group 1 exhibits generally higher WTP than the other groups, with the exception of WTP for F1. Group 4 also shows relatively high WTP compared to groups 2 and 3. The mean values of WTP for group 1 have roughly doubled compared to the WTP before grouping. In particular, group 2 shows a reduction in WTP for PC, while group 4 shows an increase in WTP for PC.

G.4.2.2 Test statistics

G.4.2.2.1 Change of WTP by group assignment

Since group assignment appears to significantly affect WTP, Wilcoxon tests are used to test whether central tendencies show significant differences before and during group assignment. The test statistics for group 1 can be taken from Table G.3, while only significant results $(p \prec 0.05)$ could be found for group 1.

	WTP (↑↓→)	Mean before	Mean after grouping	Z-Value	Significance p	Effect strength r, if significant
G1: SQ PC	↑	71	116	-3.784	< 0.001	0.60**
G1: F1	↑	42	59	-2.243	0.025	0.35
G1: F1 PC	↑	53	110	-3.970	< 0.001	0.62**
G1: F2	↑	51	105	-4.551	< 0.001	0.72**
G1: F2 PC	↑	46	105	-2.814	0.005	0.44**
G2: SQ PC	↓	50	22	-2.044	0.041	0.4**
G2: F1	-	-	-	-	0.929*	-
G2: F1 PC	↓	41	19	-2.075	0.038	0.41**
G2: F2	↓	47	32	-2.235	0.025	0.44**
G2: F2 PC	-	-	-	-	0.785*	-
G3: SQ PC	-	-	-	-	0.484*	-
G3: F1	-	-	-	-	0.052*	-
G3: F1 PC	↓	41	16	-2.366	0.018	0.45**
G3: F2	-	-	-	-	0.783*	-
G3: F2 PC	-	-	-	-	0.109*	-
G4: SQ PC	↑	37	68	-2.423	0.015	0.54**
G4: F1	-	-	-	-	0.917*	-
G4: F1 PC	↑	9	67	-3.317	< 0.001	0.74
G4: F2	↑	39	41	-2.147	0.032	0.48
G4: F2 PC	-	-	-	-	0.108*	-

* no significance; ** strong effect

Table G.3: Wilcoxon-Tests of groups

Hypothesis	Result	Proof
H1: Modal value of WTP for F1 is 0€.	confirmed	Figure G.9
H2: (Median of) WTP for F1 is around 50€.	not confirmed	Figure G.9; Median 20€ (Mean 29€)
H3: WTP for F2 is marginally higher than WTP for F1.	confirmed	Table G.5
H4: WTP for F2 is equal to sum of F1 and PC at F1.	Case-dependent, see proof	If the medians are used for the analysis, the hypothesis can be confirmed (20=20+0), whereas if the mean values are used, the hypothesis is rejected (45≠29+40) (Figure G.9). In addition, the high standard deviation should be taken into account when using the mean values.
H5: WTP for PC at F2 is close to 0€.	confirmed	Figure G.9
H6: Home ownership has a significant impact on WTP	not confirmed	Table G.6
H7: Doubts about the WTP of others have a high ranking (large influence).	not confirmed	Figure G.11

Table G.4: Hypothesis testing

All previously visually detected differences for group 1 are significant according to the tests and WTP is increasing. When examining the change in WTP for group 2 (Table G.3, G2), only the change for PC in status quo, PC at F1 and WTP for F2 are significant, with WTP decreasing. No clear conclusion can be drawn for the non-significant tests. The Wilcoxon test for group 3 (Table G.3, G3) is only significant with respect to the decreasing WTP for PC at F1. WTP for PC in status quo is significantly higher after assignment to group 4 than before (Table G.3). Examining the change in WTP of group 4, only the changes for PC in SQ and PC at F1 and WTP for F2 are significant. In these cases, the WTP increases. No clear conclusion can be drawn for the non-significant tests. The results show that group assignment affects WTP differently, with differences in terms of (S1) specific WTP and (S2) direction of effect. For group 4, WTP increases, while for group 2 it decreases.

G.4.2.2.2 Fund hypothesis testing

Our hypotheses (Section G.3.2.3) are considered mainly qualitatively and answered according to Table G.4. Thus, H1, H2, H4, H5 can be tested regarding Figure G.9 and Figure G.11, whereas H3 requires a Wilcoxon-Test (Table G.5) and H6 requires a Mann-Whitney-U-Test (Table G.6).

	WTP F1	WTP F2	WTP F3	Z-Value	Significance p	Effect strength r, if significant
F2-F1	29	45		-3.976	<0.001	0.37
F3-F1			18	-4.610	<0.001	0.43**
F3-F2		45	18	-5.875	< 0.001	0.55**

** strong effect

Table G.5: Wilcoxon-Test: differences between funds

	WTP owner	WTP renter	N	Z-Value	Significance p	Effect strength r, if significant
Sq PC	109	20	45	-3.563	<0.001	0.34 (medium)
F1 PC	79	13	45	-3.002	0.003	0.28 (weak)
F1					0.096*	
F2 PC	61	7	45	-2.511	0.012	0.24 (weak)
F2					0.367*	
F3					0.421*	

* not significant

Table G.6: Mann-Whitney-U-Test: influence of housing on WTP

A Mann-Whitney-U test is used to examine the sample divided into homeowners and renters for differences in WTP. According to the results, significant differences exist in WTP for PCs, while the state's decision (SQ, F1, F2) has only a small impact on significance: WTP for funds is not significantly different between homeowners and renters.

G.4.2.2.3 Influencing factors of WTP

Suggested influencing factors are ranked by subjects, with results shown in Figure G.11: "Distance to waterway" has the highest average influence (lowest rank 2.55) on WTP, which is followed by "Housing relationship" (2.83) and "Confidence in effective use of funds" (2.89), "Return on fund" (3.8), "Being affected in the past" (4.42) and "Doubts about others' WTP"

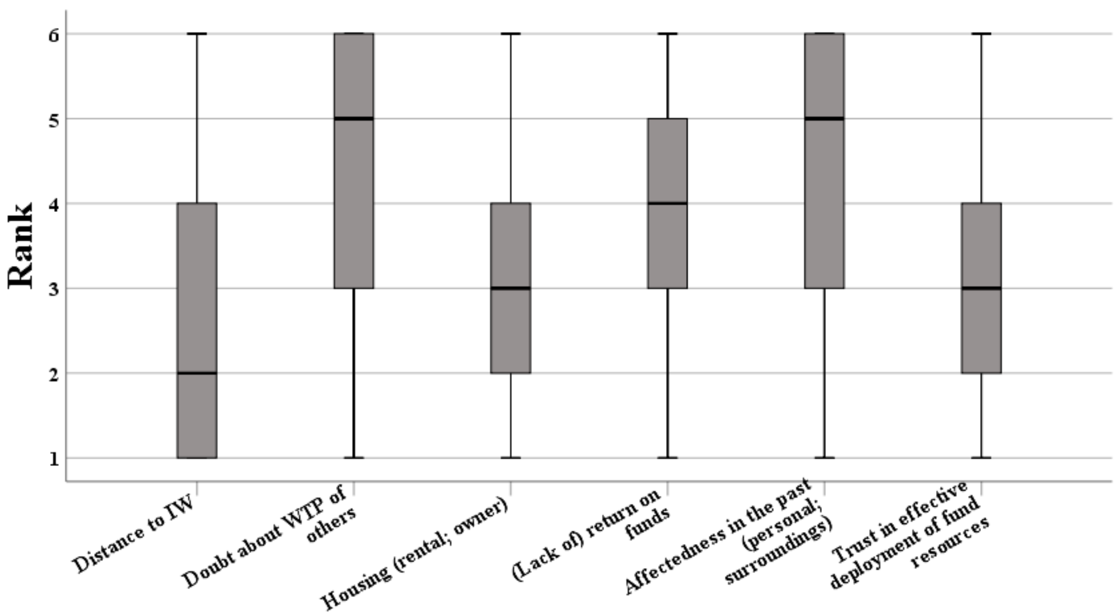

Figure G.11: Ranking of influencing factors
(high rank = low rating)

(4.5).
Doubts about others' WTP do not have a high influence on WTP, contrary to the free-rider assumption. This is presumably due to the fact that there is no threat of free riding in the literal sense: if too few people are willing to contribute, the fund cannot be set up. The lack of return on funds also only occupies the third place.

G.4.2.2.4 Likert Scales

Figure G.12 illustrates the responses to the Likert questions before and after the group assignment, with the latter being marked with the suffix "_2". The full range of response options is used for almost all questions, while it is evident that the answers rarely show major deviations from the value 3 (expected value with normal, equal distribution) in the mean value. "Knowledge of condition"(1.96), "Existential consequences"(4.35), "Consequences society"(1.96) and "Existential consequences_2"(4.65) are the extremes with deviation greater than one.
A t-test[2]to analyze differences under repeated measurements reveals significant differences between the responses given at the beginning and end of the survey; exceptions to this are the assessment of threats to waterways from climate change and from structural deterioration of dams, respectively (Table G.7).

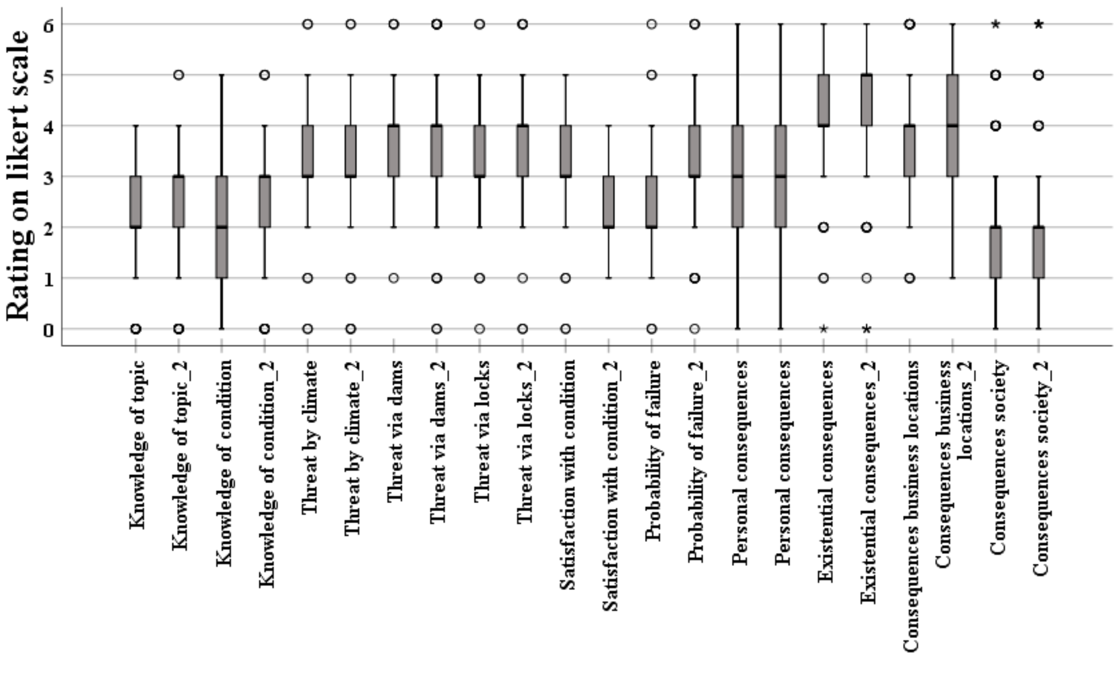

Figure G.12: Answers to Likert-scaled questions[3]

[2] Possible violation of the normal distribution assumption can be neglected with the sample size (113).
[3] "_2": repeated measure; value 0: total rejection; value 1: total approval.

Topic	Likert value	Rank before (mean)	Rank_2 (mean)	T-Value	Significance p	Effect strength r, if significant
Knowledge of topic	↑	2.14	2.53	-4.451	< 0.001	0.39
Knowledge of condition	↑	1.96	2.55	-6.656	< 0.001	0.53**
Threat by climate	-	-	-	-	*	-
Threat via dams	-	-	-	-	*	-
Threat via locks	↑	3.19	3.7	-4.984	< 0.001	0.43
Satisfaction with condition	↓	3.21	2.2	11.898	< 0.001	0.74**
Probability of failure	↑	2.38	3.39	-10.404	< 0.001	0.7**
Personal consequences	↑	2.69	2.95	-3.051	0.003	0.28 (weak)
Existential consequences	↑	4.35	4.65	-3.291	0.001	0.3
Consequences business locations	↑	3.72	3.92	-2.77	0.007	0.25 (weak)
Consequences society	↑	1.96	2.13	-2.117	0.036	0.2 (weak)

* no significance; ** strong effect

Table G.7: T-test for differences in likert questions
(N = 113)

The ratings of the threats, the probability of failure and the consequences in case of failure of the waterways increase. Only the estimation about the satisfaction with the condition of the waterways declines. The fact that 9 out of the 11 answers show significant differences, in combination with the relatively low self-assessment of knowledge of the topic(2.14) and knowledge of the condition of the waterways(1.96), suggests that there is a lack of awareness among the population, whereby reasons could be disinterest, missing perceived relevance or too high complexity of the topic.

G.4.2.3 Regression

After a general WTP for the funds and PCs has been shown and the influence of individual parameters on the WTP has been analyzed, regression models for the WTP are presented below. For the variable inclusion method, “forward and backward selection” and “stepwise” show similar results, but they will include only a few and only significant variables, thus biasing the result. Therefore, a regression model with the inclusion method is used, in which most of the variables considered relevant are included.

G.4.2.3.1 WTP for PC at Scenario 0

Since the WTP are logarithmized (Section G.4.1), the regression model is formulated according to Exp. G.1. The corresponding analysis of variance (Table G.8) shows the listed variables and that the model is significant $\left(\mathrm{F}(15,97) = 10.589,\ \mathrm{p} \prec 0.001\right)$.

$$\log(y) = \alpha + \beta_1 \cdot x_1 + \beta_2 \cdot x_2 + \cdots + \varepsilon \qquad \text{(Exp. G.1)}$$

The quality of the model, corrected R^2 (R^2), is 0.562 (0.621), resulting in an effect strength of $f^2 = 1.28$, which corresponds to a strong effect according to Cohen (1992). Furthermore, it is assumed for the interpretation that the Gauss-Markov assumptions are acceptably met.

We use the HC-3 method for the interpretation of the regression coefficients, to avoid any problems with heteroscedasticity (Hayes and Cai, 2007). The highlighted values are significant at the 0.5% level (at the 1% level with footnote). Table G.8 shows that only 5 variables exhibit a significant effect on WTP.

Using the example of the variable "WTP SQ" (query whether already paid in PC), an increase in WTP of 121.6% can be expected when the variable increases from 0 (No) to 1 (Yes). That is, a person who is already paying into PC is willing to spend 121.6% more on PC than a person who is not yet paying into PC. It should be noted at this point that these are approximate percentage changes (log-level model).

G.4.2.3.2 WTP F1 and PC

The regression model of **WTP for F1** shows significance $\left(F(15, 97) = 6.64,\ p \prec 0.001\right)$ with a quality, corrected R^2 (R^2) of $0, 43$ ($0, 507$), resulting in a strong effect ($f^2 = 0.75$).

Seven variables show statictic significance for **WTP in F1** with biggest significance of WTP for PC in case of F1 ($0, 422$) and the affectedness by floods in the environment of the respondents ($0, 375$). The regressions model for WTP in PC in case of F1 exhibits significance $\left(F(15, 97) = 8.167,\ p \prec 0.001\right)$ and a quality of the model $\left(\text{ corrected } R^2\ (R^2)\right)$ of $0, 49$ ($0, 558$), resulting in a strong effect ($f^2 = 0.96$).

Five explanatory variables have significance, with two significant only at the 1% level. WTP for PC in case of F1 has the largest significant effect (0.538). Being affected by floods in the respondents' neighborhood has no significant influence compared to the regression model for WTP in F1.

G.4.2.3.3 WTP F2 and PC

The regression models for household WTP in the scenario where F2 is introduced by the government follows. The regression model for WTP for F2 shows significance $\left(F(15, 97) = 4.236,\ p \prec 0.001\right)$. The goodness of the model, corrected R^2 (R^2), is 0.302 (0.396). Therefore, we observe a strong effect ($f^2 = 0.43$).

Among the 15 explanatory variables, four have a statistically significant influence on WTP, e.g., gender. A male respondent has a 35% lower WTP for F2 than a female respondent, while household income has a significantly lower impact(0.035). The regression model for WTP in PC for the case of the introduction of the F2 shows significance $\left(F(15, 97) = 5.266,\ p \prec 0.001\right)$, a goodness of the model, corrected R^2 (R^2), of at 0.364 (0.449) and thus a strong effect ($f^2 = 0.57$).

Only three of the variables included in the model have a statistically significant influence. The assessment of the consequences for society has a positive influence. A rating one rank higher in

	S0 PC		**F1**		**F1 PC**		**F2**		**F2 PC**		**F3**		**F1 group**	
df	15; 97		15; 97		15; 97		15; 97		15; 97		14; 98		20; 92	
F	10.589		6.64		8.167		4.236		5.266		2.019		1.792	
p	<0.001		<0.001		<0.001		<0.001		<0.001		0.024		<0.001	
R^2 (korr)	0.562 (0.621)		0.43 (0.507)		0.49 (0.558)		0.302 (0.396)		0.364 (0.449)		0.113 (0.224)		0.462 (0.558)	
f^2	1.28		0.75		0.96		0.43		0.57		0.13		0.86	
	Coeff	**Sig**	**Coeff**	**Sig**	**Coeff**	**Sig**	**Coeff**	**Sig**	**Coeff**	**Sig**	**Coeff**	**Sig**	**Coeff**	**Sig**
Personal consequences	0.008	0.919	-0.117	**0.047**	0.079	0.256	-0.024	0.743	-0.003	0.962	-0.034	0.642	-0.065	0.224
Consequences business locations	0.065	0.543	0.172	**0.027**	-0.077	0.421	0.127	0.151	-0.072	0.453	0.033	0.764	0.133	0.112
Consequences society	0.239	**0.000**	-0.157	**0.014**	0.276	**0.000**	-0.108	0.137	0.247	**0.001**	-0.019	0.808	0.056	0.296
Personal consequences	0.800	**0.001**	0.486	0.152	0.150	0.633	0.421	0.522	0.421	0.615	0.321	0.603	0.452	0.227
Surrounding affected	0.410	**0.016**	0.375	**0.007**	0.155	0.422	0.496	**0.001**	-0.045	0.821	0.335	**0.096**[b]	0.376	**0.012**
Residence (coded)	0.115	0.474	0.175	0.197	-0.271	**0.093**[b]	0.157	0.333	-0.194	0.282	0.136	0.436	0.174	0.173
Distance (coded)	-0.259	**0.040**	0.033	0.731	-0.234	**0.026**	0.033	0.787	-0.310	**0.005**	-0.024	0.843	0.016	0.869
Sex (coded)	-0.102	0.321	-0.227	**0.043**	0.086	0.516	-0.349	**0.008**	0.094	0.571	-0.165	0.226	-0.216	0.009
Income (coded)	0.025	0.265	0.035	**0.017**	0.002	0.901	0.035	**0.090**[b]	0.019	0.389	0.051	**0.015**	0.062	**0.000**
Housing	-0.208	0.227	0.125	0.428	-0.345	**0.070**[b]	0.068	0.715	-0.152	0.342	-0.050	0.780	0.081	0.590
WTP SQ	1.216	**0.000**								1.216				
WTP F1 PC log			0.422	**0.000**										
WTP F1 log					0.538	**0.000**								
WTP F2 PC log							0.365	**0.005**						
WTP F2 log								0.314	**0.019**					
Scenario 3.0													0.352	**0.043**
Scenario 4.0													-0.541	**0.002**
WTP F1 PC log group													0.139	**0.097**[b]

Table G.8: Regression Data

the Likert scale suggests 24.7% increasing WTP. Similar to the results for the regression of F1, it appears that WTP for PC has positive influence on WTP in the fund and vice versa.

G.4.2.3.4 WTP F3

The model shows significance $\left(\mathrm{F}(14, 98) = 2.019,\ \mathrm{p} = 0.024\right)$ and a quality of R^2 $(\mathrm{R}^2) = 0.113$ (0.224). This results in a weak effect $(\mathrm{f}^2 = 0.13)$. Thus, the regression model for F3 seems to have only a limited fit. Without prejudice to the discussion, it can be seen that the goodness and effect size are low, especially compared to the regression models for F1 and F2. The significance level of the model is also much weaker, with only two explanatory variables having a significant effect, one of the two only at the 1% level. Household income (0.051) and being affected by floods in the respondents' neighborhood (0.335) have an explanatory influence.

G.4.2.3.5 WTP F1 with group assignment

Finally, an exemplary regression model follows, which takes into account the scenarios of assignment to a group, therefore dummy variables for the corresponding groups are added to the model. In addition, the dichotomous variables of influence (Yes, No) with respect to employer and place of residence are included in the model. The coefficients lack information regarding the dummy variables for assignment to group 1 (scenario=1.0). This is to be expected, since one of the dummy variables can be mapped over the others and is therefore excluded from the model (if it is not dummy-2, -3, or -4, it follows that it is dummy-1).

The model shows significance $\left(F(20, 92) = 5.802,\ p \prec 0.001\right)$. The goodness of the model, corrected R^2 (R^2), is 0.462 (0.558). Therefore, a strong effect results ($f^2 = 0.86$).

Six of the included variables have a significant influence on the independent variable. “Surrounding affected” and “ WTP F1 PC log Group” are significant, as for the data without group assignment, with a positive influence on WTP. The dummy variables (group assignment) have a significant influence for groups 3 and 4. This is also confirmed by the Wilcoxon tests.

The multi-collinearity test is performed using the data in Table G.8. It can be seen that all variance inflation factor values are below 10, more precisely below 3, and thus there is no problem due to multi-collinearity (Wooldridge, 2013).

G.5 Discussion

G.5.0.1 Findings

In summary, the funds can be financed by households and, an improvement in the overall situation can be generated by a fund. The WTP of households for the three funds differs. In the survey, F1 receives a mean (median) WTP of about 29€ (20€), i.e., below the WTP for F2 with 45€ (20€), and above the WTP for F3 with 18€ (10€). Compared to the values of WTP of similar studies (64-69, 30-76, 36-148, 50, 315; Entorf and Jensen, 2020), the mentioned WTP turn out to be low. Influences for the lower WTP may lie in the low awareness of the waterway, as well as the timing of the survey, which is in the midst of the COVID-19 pandemic, bringing with it poor economic conditions.

A general WTP for the public good is measurable; it contradicts theoretically expected behavior according to game theory, but is consistent with behavior measured in experiments. The difference of the WTP F2 to F1 apparently (no test performed) does not correspond to the WTP for PC. It can therefore be concluded that respondents trust the insurance component of F2 less than private coverage, or exploit the insurance coverage. Exploitation is possible because no distinction is made with respect to the amount of the deposit in F2, and thus a WTP of€1 provides as good “insurance protection” as a specification of the real WTP, which is presumably higher. However, since the specification of WTP for PC in the case of F2 is close to zero, it is rather assumed that the insurance component is exploited. For lack of trust as a cause, higher PC is expected. Other influences not considered here are also conceivable. Regardless of the cause for the slightly higher WTP for F2, an adjustment must be made or the additional cost of insurance will not be covered.

A possible reason for the low WTP for F3 could be that the objectives are not clear enough or are perceived as too general. The Wilcoxon tests regarding group assignment show that the considered influence variables “dependence of employer” and “distance of residence to waterway” are relevant. The influence “distance of the place of residence to the waterway” clearly predominates. This can be seen from the fact that the direction of action (increasing, decreasing WTP) is reversed if “dependence of the employer” is kept constant and “distance of the place of residence to the waterway” is varied. Conversely, if “distance of residence to waterway” is kept constant, there is no reversal of the direction of action. The fact that “one’s own home appears more important than one’s employer” is intuitively understandable (high, direct financial damage and emotional loss), but cannot be justified in more detail here.

An examination of the coefficients of the regression models for F1 and F2 shows that they differ from each other. For both funds, having been affected by floods in the past, gender and household income have a significant influence. For F1, the assessment of the Likert questions regarding the threat (due to failure of the waterway) to one’s own existence, individual economic locations and society are additionally significant.

Household size, place of residence (urban, rural), and home ownership have no significant influence in the regressions, in contrast to the data from Entorf and Jensen (2020) who also point out that age, gender, and education are significant in other studies. In this paper, this statement can only be confirmed for the influence of gender. The influence of home ownership on WTP for PC is not found in the regression models of WTP for funds. Also, the distance of the home from the waterway does not show significance in the regression models for F1 and F2, which is inconsistent with the Wilcoxon tests.

G.5.0.2 Limitations

Due to the complexity and elusiveness of the topic, in combination with many hypothetical questions, the WTP estimates for a hypothetical fund with abstract implications can hardly be equated with realistic payments, but mainly show tendencies in comparison to each other.

The implementation of the survey could also be optimized by repeated surveys, an increase in the number of participants; furthermore, a professional pilot survey for feedback and validation, consolidation of the queried items can be considered. Although the overall models show significance, many of the parameters included do not. The reasons for this may be violations of the Gauss-Markov assumptions or other explanatory variables that have not been taken into account. One potential violation of the Gauss-Markov assumptions is that the sample taken is not random. The sample data comes from a social fabric, therefore, a non-representative homogeneity can be suspected.

Few studies and regressions have been conducted in this specific research area resulting in a lack of comparative values and references. Additionally, it is difficult to identify clear, causally based relationships and thus influencing variables in the complex context. However, an added value by the findings obtained here is nevertheless given as the basic interrelationships are still accessible.

G.5.0.3 Remark on the role of trust

While the WTP for risk reduction classically depends on the population's perception of risk (Birkholz et al., 2014; Bubeck et al., 2012), the WTP for efficient use of funds to strengthen infrastructure depends much more strongly on citizens' trust in the state and in the efficiency and reliability of public services of general interest. The Scandinavian countries, for example, traditionally place a larger share of public services in the hands of the state and at the same time have an above-average level of trust in the state and public institutions (Marozzi, 2015; Yamamura, 2014).

However, trust is not only a prerequisite, but also a potential gain from such a fund initiative. Involving citizens in the financing of public infrastructure promotes their interest, awareness and also their knowledge of infrastructure-related risks. The transparency of the financing and decision-making processes that comes with a public fund also contributes to this (Mabillard and Pasquier, 2018).

G.6 Conclusion and Outlook

The survey data show a WTP for the funds and waterways. Overall, additional financial resources under the funds can make a positive contribution to overall societal benefits, if deficit of alongside mechanisms (Section G.2.4) are addressed at least in the long term. Infrastructure funding problems can thus be circumvented or mitigated. The regression models of the funds show and confirm significant influences on WTP.

These findings indicate that citizen participation in infrastructure financing through infrastructure funds, if implemented, is both financially feasible and could provide benefits. The problems of waterway financing can be averted in the medium term, so further investigation in this research area is recommended.

The problems and deficiencies addressed provide a good basis for follow-up research and investigation. Verification of the findings here with a larger data set is recommended. In addition, further influences, with presumed gains in knowledge, should be included in a renewed survey.

A point for further investigation is the compatibility of the fund models with existing legal regulations. The feasibility of the measures was assumed in the paper for simplicity and needs to be examined for any more realistic considerations. The modeling of the impact of the funds on waterway financing needs additional research, as the established evidence in this area needs to be supplemented.

Acknowledgments

The authors want to thank the partners in the joint research project for Digital and Transport (2018). The project is funded by the security research program (www.sifo.de) of the German Federal Ministry of Education and Research (BMBF; grant number 13N14697). Special thanks goes to Jan-Niklas Borcherding.

References

Akkermann, J., Weiler, S., Bödefeld, J., Marsili, F. (2020). Vulnerabilität von Verkehrswasserbauwerken.

Baird, A. J. (2013). Acquisition of UK Ports by Private Equity Funds. *Research in Transportation Business & Management*, *8*(2), 158–165.

Bardt, H., Chrischilles E., Fritsch M., Grömling M., Puls T., Röhl K.- H. (2014). Die Infrastruktur in Deutschland: Zwischen Standortvorteil und Investitionsbedarf: IW-Analysen. (95).

Beckers, T., Bieschke, N., Lenz, A. K., Heurich, J., Kühling, J., Hertel, W., Schäfer, D. (2014). *Alternative Modelle für die Organisation und die Finanzierung des Ausbaus der Stromübertragungsnetze in Deutschland: Eine (institutionen-) ökonomische Analyse unter Einbezug juristischer und technisch-systemischer Expertise.* Berlin/Regensburg.

Behrendt, F., Trojahn, S. (2013). Herausforderung für die Zukunft - nachhaltige und solide Verkehrsinfrastrukturfinanzierung. *18. Magdeburger Logistiktage - Sichere und nachhaltige Logistik*.

Bianchi, R. J., Bornholt, G., Drew, M. E., Howard, M. F. (2014). Long-term U.S. Infrastructure Returns and Portfolio Selection. *Journal of Banking & Finance*, *42*(7), 314–325.

Birkholz, S., Muro, M., Jeffrey, P., Smith, H. M. (2014). Rethinking the relationship between flood risk perception and flood management. *The Science of the total environment*, *478*, 12–20.

Bitsch, F., Buchner, A., Kaserer, C. (2010). Risk, Return and Cash Flow Characteristics of Infrastructure Fund Investments.

Brancato, G., Macchia, S., Murgia, M., Signore, M., Simeoni, G., Blanke, K., Hoffmeyer-Zlotnik, J. (2006). Handbook of Recommended Practices for Questionnaire Development and Testing in the European Statistical System.

Bubeck, P., Botzen, W., Kreibich, H., Aerts, J. (2013). Detailed Insights Into the Influence of Flood-Coping Appraisals on Mitigation Behaviour. *Global Environmental Change*, *23*(5), 1327–1338.

Bubeck, P., Botzen, W. J. W., Aerts, J. C. J. H. (2012). A review of risk perceptions and other factors that influence flood mitigation behavior. *Risk Analysis*, *32*(9), 1481–1495.

Chou, J.-S., Pramudawardhani, D. (2015). Cross-Country Comparisons of Key Drivers, Critical Success Factors and Risk Allocation for Public-Private Partnership Projects. *International Journal of Project Management*, *33*(5), 1136–1150.

Cohen, J. (1992). A Power Primer. *Psychological Bulletin*, *112*(1), 155–159.

Cohen, J., Kamga, C. (2013). Financing High Speed Rail in the United States and France: The Evolution of Public-Private Partnerships. *Research in Transportation Business & Management*, *6*(March), 62–70.

Coleman, A., Grimes, A. (2010). Betterment Taxes, Capital Gains and Benefit Cost Ratios. *Economics Letters*, *109*(1), 54–56.

Cui, C., Liu, Y., Hope, A., Wang, J. (2018). Review of Studies on the Public-Private Partnerships (PPP) for Infrastructure Projects. *International Journal of Project Management*, *36*(5), 773–794.

Daehre, K.-H. (Ed.). (2012). *Zukunft der Verkehrsinfrastrukturfinanzierung: Bericht der Kommission.*

Dunn-Cavelty, M., Suter, M. (2009). Public-Private Partnerships are No Silver Bullet: An Expanded Governance Model for Critical Infrastructure Protection.

Entorf, H., Jensen, A. (2020). Willingness-to-Pay for Hazard Safety - A Case Study on the Valuation of Flood Risk Reduction in Germany. *Safety Science*, *128*, 104657.

Eurodad. (2020). *Why Public-Private Partnerships (PPPs) Are Still Not Delivering.* Retrieved from http://www.eurodad.org/why_public_private_partnerships_are_still_not_delivering

Falkinger, J., Fehr, E., Gächter, S., Winter-Ebmer, R. (2000). A Simple Mechanism for the Efficient Provision of Public Goods: Experimental Evidence. *American Economic Review*, *90*(1), 247–264.

Fandel, G., Giese, A., Mohn, B. (2012). Measuring Synergy Effects of a Public Social Private Partnership (PSPP) Project. *International Journal of Production Economics*, *140*(2), 815–824.

Federal Agency for Civic Education of Germany (Ed.). (2022). *Bevölkerung nach Altersgruppen und Geschlecht. Bundeszentrale Für Politische Bildung.* Retrieved from http://www.bpb.de/kurzknapp/zahlen-und-fakten/soziale-situation-in-deutschland/61538/bevoelkerung-nachaltersgruppen-und-geschlecht/

Federal Environment Agency of Germany UBA (Ed.). (2021). *Emissionsdaten.* Retrieved from http://www.umweltbundesamt.de/themen/verkehrlaerm/emissionsdaten#verkehrsmittelvergleich_personenverkehr_grafik

Federal Ministry for Digital and Transport (Ed.). (2014). VV-WSV 1102 Objektkatalog: Verwaltungsvorschrift der Wasserstraßen- und Schifffahrtsverwaltung des Bundes.

Federal Ministry for Digital and Transport (Ed.). (2015). Verkehrsinfrastrukturbericht.

Federal Ministry for Digital and Transport (Ed.). (2016). Bundesverkehrswegeplan 2030.

Federal Ministry for Digital and Transport (Ed.). (2019). Masterplan Binnenschifffahrt.

Federal Ministry for Digital and Transport (Ed.). (2021). Verkehr in Zahlen 2020/2021. (47).

Federal Ministry of Finance of Germany (Ed.). (2021). *Die Struktur des Bundeshaushaltes.* Retrieved from http://www.bundeshaushalt.de/#/2021/soll/ausgaben/einzelplan/1203.html

Federal Statistical Office of Germany (Ed.). (2020). *Volkswirtschaftliche Gesamtrechnungen: Input-Output-Rechnung nach 12 Gütergruppen / Wirtschafts- und Produktionsbereichen: 2017 (Revision 2019, Stand: August 2020).* Retrieved 12.01.2022, from http://www.destatis.de/DE/Themen/Wirtschaft/Volkswirtschaftliche-Gesamtrechnungen-Inlandsprodukt/Publikationen/Downloads-Input-Output-Rechnung/input-output-12-guetergruppen-pdf-5815117.html

Federal Statistical Office of Germany (Ed.). (2022). *Daten zur Verkehrsinfrastruktur, wie zum Beispiel Straßenlängen für die Jahre 2017 bis 2021: Verkehrsinfrastruktur in Deutschland (1 000 Kilometer).* Retrieved from http://www.destatis.de/DE/Themen/Branchen-Unternehmen/Transport-Verkehr/Unternehmen-Infrastruktur-Fahrzeugbestand/Tabellen/verkehrsinfrastruktur.html

Fichert, F. (2017). Transport Policy Planning in Germany - An Analysis of Political Programs and Investment Masterplans. *European Transport Research Review*, *9*(2).

Francis, R., Bekera, B. (2014). A Metric and Frameworks for Resilience Analysis of Engineered and Infrastructure Systems. *Reliability Engineering & System Safety*, *121*, 90–103.

GDV (Ed.). (2021). *„ZÜRS Geo" - Zonierungssystem für Überschwemmungsrisiko und Einschätzung von Umweltrisiken.* Retrieved from http://www.gdv.de/de/themen/news/-zuers-geozonierungssystem-fuer-ueberschwemmungsrisiko-und-einschaetzung-von-umweltrisiken-11656

Geekiyanage, D., Fernando, T., Keraminiyage, K. (2020). Assessing the State of the Art in Community Engagement for Participatory Decision-Making in Disaster Risk-Sensitive Urban Development. *International Journal of Disaster Risk Reduction : IJDRR*, *51*, 101847.

Gemson, J., Annamalai, T. R. (2015). A new Perspective on Private Equity Stage Financing: Evidence from Investments in Infrastructure. *Venture Capital*, *17*(4), 299–325.

Gemson, J., Gautami, K. V., Thillai Rajan, A. (2012). Impact of Private Equity Investments in Infrastructure Projects. *Utilities Policy*, *21*(4), 59–65.

Givens, A. D., Busch, N. E. (2013). Realizing the Promise of Public-Private Partnerships in U.S. Critical Infrastructure Protection. *International Journal of Critical Infrastructure Protection*, *6*(1), 39–50.

Große Hüttmann, M., Wehling, H.-G. (Eds.). (2013). *Das Europalexikon: Begriffe, Namen, Institutionen* (2nd ed.). Bonn: Dietz.

Hayes, A. F., Cai, L. (2007). Using Heteroskedasticity-Consistent Standard Error Estimators in OLS Regression: An Introduction and Software Implementation. *Behavior Research Methods*, *39*(4), 709–722.

Heitmann, N., Rehdanz, K., Schmidt, U. (2013). Determining Optimal Transit Charges: The Kiel Canal in Germany. *Journal of Transport Geography*, *26*(2006), 29–42.

Helfrich, S. (2014). Gemeingüter sind nicht, sie werden gemacht. In S. Helfrich Heinrich-Böll-Stiftung (Eds.), *Commons* (pp. 85–91). transcript Verlag.

Hossain, N. U. I., Nur, F., Hosseini, S., Jaradat, R., Marufuzzaman, M., Puryear, S. M. (2019). A Bayesian Network Based Approach for Modeling and Assessing Resilience: A Case Study of a Full Service Deep Water Port. *Reliability Engineering & System Safety*, *189*(1), 378–396.

Houlihan, B. (1994). Europe's Ageing Infrastructure. *Utilities Policy*, *4*(4), 243–252.

Hüttelmaier, T., Käser, B., Akkermann, J., Weiler, S. (2019). Mehrdimensionale Risiken und Gefährdungen durch Instandsetzungsstau bei Verkehrsinfrastrukturen. *Bevölkerungsschutz*(4), 28–33.

Kapesa, T., Mugano, G., Fourie, H. (2021). Financing Public Infrastructure in Zimbabwe: Current Trends and Future Alternatives. *Public and Municipal Finance*, *10*(1), 82–93.

Kleine, J., Krautbauer, M., Schulz, T. C. (2015). Infrastrukturinvestments – Übersicht über eigen- und fremdkapitalbasierte Anlagemöglichkeiten. In J. Kleine, T. C. Schulz, M. Krautbauer (Eds.), *Infrastrukturinvestments* (Vol. 18, pp. 81–100). Wiesbaden: Springer Fachmedien Wiesbaden.

Klockow, S., Hofer, W. (1991). Improvement of Road Maintenance Practices in Developing Countries: Case Study from Nepal. *Transportation Research Part A: General*, *25*(2-3), 113–120.

Kopper, C., Gawel, E., Hartwig, K. H., Rothengatter, W., Eisenkopf, A. (2013). Die Verkehrsinfrastruktur in Deutschland: Marode und unterfinanziert. *Wirtschaftsdienst*(10), 659–677.

Kumari, A., Kumar Sharma, A. (2017). Infrastructure Financing and Development: A Bibliometric Review. *International Journal of Critical Infrastructure Protection*, *16*, 49–65.

Lenz, S. (2009). *Vulnerabilität kritischer Infrastrukturen.*

Mabillard, V., Pasquier, M. (2018). Transparency and trust in government: A two-way relationship. *Yearbook of Swiss Administrative Sciences*, *6*(1), 23.

Marozzi, M. (2015). Measuring trust in european public institutions. *Social Indicators Research*, *123*(3), 879–895.

Mishra, S., Khasnabis, S., Swain, S. (2013). Multi-Entity Perspective Transportation Infrastructure Investment Decision Making. *Transport Policy*, *30*(267–274), 1–12.

Moles, P., Williams, G. (1995). Privately Funded Infrastructure in the UK: Participants' Risk in the Skye Bridge Project. *Transport Policy*, *2*(2), 129–134.

Morasch, K., Tóth, R. O. (2008). *Assigning Tasks in Public Infrastructure Projects: Specialized Private Agents or Public Private Partnerships?* (Vols. Jg. 20, Nr. 2). Neubiberg: Inst. für Volkswirtschaftslehre.

Moss, T. (2011). *Planung technischer Infrastruktur für die Raumentwicklung: Ansprüche und Herausforderungen in Deutschland* (Vol. Bd. 235). Hannover.

Mostafavi, A., Abraham, D., Vives, A. (2014). Exploratory Analysis of Public Perceptions of Innovative Financing for Infrastructure Systems in the U.S. *Transportation Research Part A: Policy and Practice*, *70*(4), 10–23.

Njoh, A. J. (2011). Municipal Councils, International NGOs and Citizen Participation in Public Infrastructure Development in Rural Settlements in Cameroon. *Habitat International*, *35*(1), 101–110.

OECD. (2020). *Financing Water Supply, Sanitation and Flood Protection.*

Osberghaus, D. (2015). The Determinants of Private Flood Mitigation Measures in Germany - Evidence from a Nationwide Survey. *Ecological Economics*, *110*(1), 36–50.

Oztanriseven, F., Nachtmann, H. (2020). Modeling Dynamic Behavior of Navigable Inland Waterways. *Maritime Economics & Logistics*, *22*(2), 173–195.

Panayiotou, A., Medda, F. R. (2014). Attracting Private Sector Participation in Transport Investment. *Procedia - Social and Behavioral Sciences*, *111*, 424–431.

Peng, M., Zhang, L. M. (2012). Analysis of Human Risks due to Dam-Break Floods - Part 1: A New Model Based on Bayesian Networks. *Natural Hazards*, *64*(1), 903–933.

Post, A. E., Murillo, M. V. (2016). How Investor Portfolios Shape Regulatory Outcomes: Privatized Infrastructure After Crises. *World Development*, *77*(1), 328–345.

PwC (Ed.). (2016). *Rechtliche und institutionelle Voraussetzungen zur Einführung neuer Formen zur privaten Finanzierung öffentlicher Infrastrukturvorhaben unter Einbindung einer staatlichen Infrastrukturgesellschaft: Gutachterliche Stellungnahme für das Bundesministerium für Wirtschaft und Energie.* Berlin. Retrieved from http://www.bmwi.de/Redaktion/DE/Downloads/Studien/pwc-gutachtenlang.%20pdf?__blob=publicationFile&v=6

Ramamurti, R. (2003). Can Governments Make Credible PROMISES? Insights from Infrastructure Projects in Emerging Economies. *Journal of International Management*, *9*(3), 253–269.

Rand, D. G., Nowak, M. A. (2013). Human Cooperation. *Trends in Cognitive Sciences*, *17*(8), 413–425.

Rohács, J., Simongáti, G. (2007). The Role of Inland Waterway Navigation in a Sustainable Transport System. *Transport*, *22*(3), 148–153.

Samuelson, P. A. (1954). The Pure Theory of Public Expenditure. *The Review of Economics and Statistics*, *36*(4), 387.

Spegel, E. (2017). Valuing the Reduction of Floods: Public Officials' versus Citizens' Preferences. *Climate Risk Management*, *18*, 1–14.

Statista (Ed.). (2013). *Meinung zur Pkw-Maut in Deutschland: Soll eine Autobahn-Maut für PKW eingeführt werden?* Retrieved from http://de.statista.com/statistik/daten/studie/70861/umfrage/meinungzur-%20pkw-maut-in-deutschland/

Statista (Ed.). (2021). *Anzahl der beschäftigten Schiffsführer Binnen-, Hafenverkehr in Deutschland in den Jahren 2012 bis 2020.* Retrieved from http://de.statista.com/statistik/daten/studie/203016/umfrage/anzahl-der-beschaeftigtenbinnenschiffer-%20in-deutschland/

Statista (Ed.). (2022). *Durchschnittsalter der Bevölkerung in Deutschland nach Staatsangehörigkeit 2019 | Statista.* Retrieved from http://de.statista.com/statistik/daten/studie/723069/umfrage/durchschnittsalter-derbevoelkerung-in-deutschland-nach-staatsangehoerigkeit/

Sturm, J.-E., Jacobs, J., Groote, P. (1999). Output Effects of Infrastructure Investment in the Netherlands, 1853 - 1913. *Journal of Macroeconomics*, *21*(2), 355–380.

Tonn, G., Reilly, A., Czajkowski, J., Ghaedi, H., Kunreuther, H. (2021). U.S. Transportation Infrastructure Resilience: Influences of Insurance, Incentives, and Public Assistance. *Transport Policy*, *100*(4), 108–119.

Wehrle, R., Wiens, M., Schultmann, F. (2022). Evaluation of the Potential of Infrastructure Funds using the Case of Inland Waterways.

Wehrle, R., Wiens, M., Schultmann, F., Akkermann, J., Bödefeld, J. (2020). Ebenensystem zur Resilienzbewertung kritischer Verkehrsinfrastrukturen am Beispiel der Wasserstraßen. *Bautechnik*, *97*(6), 395–403.

Yamamura, E. (2014). Trust in government and its effect on preferences for income redistribution and perceived tax burden. *Economics of Governance*, *15*(1), 71–100.

Yildiz, Ö. (2014). Financing Renewable Energy Infrastructures via Financial Citizen Participation - The Case of Germany. *Renewable Energy*, *68*, 677–685.

Zhang, Y. (2014). From State to Market: Private Participation in China's Urban Infrastructure Sectors, 1992 - 2008. *World Development*, *64*(2), 473–486.

Zio, E. (2016). Challenges in the Vulnerability and Risk Analysis of Critical Infrastructures. *Reliability Engineering & System Safety*, *152*, 137–150.