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On the influence of infrastructure availability on companies decisions toward modal shift and relocation of falicities

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ABSTRACT

Purpose: Reduced availability of transport infrastructure affects highly dependent global supply chains (SCs), leading to modal shifts in the short term. Since relocation decisions of facilities may result in the long term, this paper evaluates companies' business decisions in reaction to availability reductions of inland waterway transport (IWT).
Methodology: A transport model evaluates the impact of reduced infrastructure availability through heuristic optimization based on the Traveling Purchaser Problem. The resulting increase in operational costs is used to assess the probability of relocating facilities based on a Facility Location Problem (FLP) which enables deriving the benefit from infrastructure conditions.
Findings: The study identifies critical thresholds for infrastructure availability that affect companies' relocation decisions regarding the maintenance of public infrastructure. The case study exhibits actual critical infrastructure assets.
Practical implications: Insights into the decisive consequences of companies' decisions are given, and awareness of the relevance of infrastructure investments on local areas' attractiveness is raised. The results imply considering public infrastructure investments in maintenance for private business locations.
Originality: The paper highlights a new way to sustain local industries and connects short-term agility and long-term resilience with companies' decisions and the exogenous factor infrastructure availability. The applied use case focuses on the barely studied waterway infrastructure that gains importance in light of sustainability and climate change.

1. Introduction

As transport infrastructure is often undersized (leading to congestion) and outdated (leading to deterioration and failures), infrastructure failure leads to disruptions in logistics operations (Stewart et al., 2011, Manfredi et al., 2018, Kotowska et al., 2018, An et al., 2015). This impairs global Supply Chains (SCs) which are increasingly vulnerable to disruptions due to their inherently complex and global interdependencies (Doorly, 2020); while increasing risks in the world (Forum, 2021) pose the threat of escalating SC disruptions, endangering economic welfare. Therefore, this paper identifies the necessity to analyze and improve the resilience capacities of SCs (Ivanov, 2020, Hosseini et al., 2019, Witt, 2019) in relation to certain exogenous conditions since the public sector generally bears responsibility for the provision, planning, and upkeep of transportation infrastructure (Essen et al., 2020, Li et al., 2019).

For companies, these exogenous conditions constitute a dilemma: Although their operations depend on the permanent availability of public infrastructure, they have neither direct influence on maintenance and expansion decisions nor can they ensure timely transmission of information about short-time availability and status of transportation infrastructure (Li et al., 2019). These additional costs can outweigh revenue, making operations unsustainable.

Considering that ensured access to available transportation infrastructure is one of the essential factors for business locations (Mejia-Dorantes et al., 2012, Rezaei et al., 2018), facility relocation might

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become preferable. In this context, investment in the maintenance of public infrastructure is central yet under-acknowledged within the existing literature on private sector reaction. However, the public and private sectors are responsible for the resilience of private global SCs, while infrastructure availability can support domestic business locations.

Enhancing resilience necessitates the cooperation and shared responsibility of both government and private sector in transportation infrastructure, as is the case already in specific domains of critical infrastructures (Trucco and Petrenj, 2017). Nevertheless, this is different for inland waterways (IWs), where the public sector holds the sole responsibility for investments and thus the availability of the infrastructure (Li et al., 2019). Furthermore, IW infrastructure presents an illustrative case study, as it has been identified as a potential constraint on industry supply, characterized by the transport of high-volume goods via a wide-meshed yet redundant transport network for specific industries (European Court of Auditors, 2015), i.e., construction, chemical, and energy (see Destatis, 2019). However, despite expanding literature on the impact of transportation infrastructure on SC resilience, little attention has been paid to the specific context of inland waterway transport (IWT).

Specific works regarding links between IW infrastructure and Supply Chain Risk Management (SCRM) exist. For example, MacKenzie et al. (2012) analyze the consequences of IW port closures and state that the modal shifts to rail cargo are the most likely company decision as a reaction due to the similar scalability of bulk good transport. Pant et al. (2015), moreover, investigate disruptions of IW infrastructure in case of, among others, a two-week port disruption and highlight the multiregional industrial interdependencies. Beuthe et al. (2001) analyze intermodal freight transport based on GIS networks, considering demand elasticities. However, elaborations on the costs of IWT in the intermodal context, as contributed by Wiegmans and Konings (2015) or Hintjens et al. (2020), are scarce. To the best of the authors' knowledge, no work considers the link between SC performance and the availability of IWT infrastructure. Yet, this link enables the anticipation of companies' decisions in the short term and the long run relevant for public investments in the infrastructure conditions. Hence, this paper states the research question:"How does infrastructure availability influence companies' decisions toward modal shift and relocation of facilities?".

This paper aims for a valid method to connect long-term infrastructure availability, location decisions, and short-term logistics decisions to answer the research question. 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 essential factor in logistics performance (Rezaei et al., 2018). The chosen use case focuses on a less explored type of infrastructure, specifically IWs. On the one hand, IWs are challenged by climate change and infrastructure degradation; on the other hand, IWT is a sustainable mode of transport necessary in achieving climate goals (BMDV, 2016).

From a methodological perspective, the study combines a Traveling Purchaser Problem (TPP) as a transport model and a Facility Location Planning (FLP) model for a relocation decision linked to transportation infrastructure. The first model analyzes the influence of infrastructure availability on companies' decisions toward modal shift using a Vehicle Routing Problem approach and the possibility of relocating whole facilities using an FLP formulation. The short-term operational logistics model (TPP) output provides the impact of transport costs caused by infrastructure unavailability obstructing navigation due to failures or maintenance. This output, in turn, is the input for the second model (FLP) of long-term strategic decisionmaking, determining the probability of relocating. Furthermore, the extension by a cost-driven utility function allows for assessing the value of transport infrastructure availability for businesses. Lastly, the developed econometric model is applied to waterway transport in the West German Canal Network (WGCN), focusing on the chemical industry using public data on transportation volumes and infrastructure availability.

In particular, the analysis identifies a promising opportunity to enhance domestic business locations by increasing the infrastructure availability of IWT. While recent literature on public policies of regional development focuses on attracting new industries or firms, the provided approach takes a downside perspective by determining the"threshold of pain" of infrastructure conditions which motivates firms to make the consequential decision to leave the area, respectively relocate investments.

The remainder of the paper is organized as follows: Section 2 classifies the research question according to the literature, specifically in the subject areas of SCRM, FLP, and infrastructure availability as a location factor. Section 3 presents the research approach, the formulation of the operational transport model (short term-focus), and the strategic relocation model (long term-focus). Next, section 4 applies the approach to a case study of the WGCN and the chemical industry as a key private stakeholder dependent on public investments in the IW infrastructure. Section 5 summarizes and discusses the findings, and section 6 closes the elaboration with concluding remarks.

2. Literature review

2.1. Supply chains and infrastructure as exogenous factor

SCs are vital to the economy and are influenced by various factors, including infrastructure availability and accessibility. This section discusses the impact of these exogenous factors on SCs and their implications for strategic decision-making. SCs interact with their environment in complex ways, triggered by mutual interrelations and feedback between themselves, nature, society, and the economy (Ivanov, 2020). They consist of interconnected firms with connections represented by flows of materials, information, and finance (Carter et al., 2015, Mentzer et al., 2001).

2.1.1. Supply Chain disruptions

SCs can be permanently disrupted due to various causes, for instance, pandemics (Chowdhury et al., 2021, Choi, 2021), terrorist attacks, labour strikes, human error and 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 is relatively low. Furthermore, they can either be independent of each other (e.g., a fire event in a particular 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 Supply Chain Management (SCM) (and even FLP as a specific approach; see section 2.3) that account for disruptions (e.g. Snyder et al., 2016, Snyder and Daskin, 2005, Cui et al., 2010). As stated before, today's SCs face multiple risks since manifold external forces endanger business continuity (Christopher, 2016). However, empirical studies on SC disruptions are still overly focused on single events and anecdotal evidence. Therefore, systematic assessments of SC disruptions and their effects are characterized by instead few evidence-based approaches due to the lack of data (Chowdhury et al., 2021). Choi (2021) also highlights the need for systematic analyses of logistics within vulnerable complex systems-of-systems (Eusgeld et al., 2011).

Effective SCRM is indispensable as part of SCM (Bugert and Lasch, 2018) to mitigate increasing risks. Complementary approaches predominantly focus on SC design (Wu et al., 2007, Yu et al., 2009, Hosseini et al., 2019, Tirkolaee et al., 2020, Garcia and You, 2015, Shabbir et al., 2021) thereby neglecting the implications of short-term disruptions and external effects in the long run.

2.1.2. Infrastructure availability and accessibility

External effects can originate from transport infrastructure which

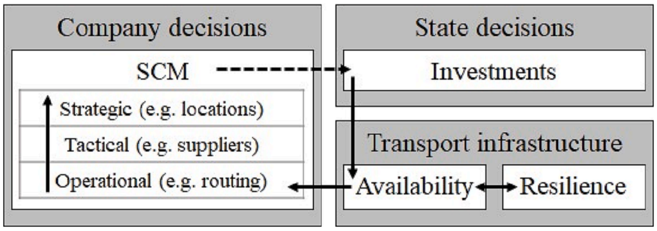

Fig. 1. Context of decisions.

must be accessible and available to ensure reliable use. While accessibility is determined by local conditions and the geographical location of the infrastructure (De Bok, 2009), literature uses various proxies to interpret availability: Zepeda Ortega et al. (2019) use road density as a measure of the availability of road infrastructure which is instead attributable to accessibility. Sullivan et al. (2010) link network performance to changes 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.

Thereby, the term availability 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) provide an availability assessment model for IWs 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 expression (1):

$$A = \frac{MTBF}{MTTR + MTBF} \tag{1}$$

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).

The availability of transport infrastructure is of particular interest in the context of SCRM due to the multiple dependencies within and among SC agents (Heckmann et al., 2015). However, applying quantitative, context-sensitive models emphasizing 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). The analysis of available transport links within SC networks primarily comprises network trip robustness and has only been used in transportation planning but not in FLP (Andronov and Jurkina, 2015, Taghizadeh and Hafezi, 2012). As further research efforts should explore the link between the availability of infrastructure at specific geo-locations and strategic SCRM decisions from a modeling side, this paper contributes to this gap as laid out by Li et al. (2016).

2.2. Towards strategical implications

Melo et al. (2009) provide a short review of the planning levels of SCM (Fig. 1, 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 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).

While reliability, resilience, and disruptions are closely linked in the literature but mainly pertaining to the reliability of suppliers rather than the reliability of transport infrastructure (Tomlin, 2006, Linnenluecke, 2017, Dolgui et al., 2018, Cavalcante et al., 2019). Overall, the availability of IW infrastructure assets is affecting SCs in the long term due to the combination of repair backlogs, maintenance durations, and scarce resources in infrastructure construction (Wehrle et al., 2022a).

Fig. 1 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 low and the targeted shortterm measures have to be taken repeatedly, the operational risk of infrastructure failure (i.e., lock closure) affects the strategic level. However, if availability remains low and short-term measures have to be taken repeatedly, the operational risk of infrastructure failure affects the strategic level.

Snyder et al. (2016) identifies FLP as a possible measure to mitigate disruptions. This implies the existence of a critical threshold and the question of at what point a short-term measure like modal shift influences strategic decisions such as the planning of facility locations. This threshold of pain is the point at which economic operations become unfeasible as operating costs surpass operating profit. While logistics costs usually don't have a high cost share in final products, logistics costs of the base chemical industry are at around 8% (Schwemmer et al., 2020). If the profit margins are around 4\% and transport costs double due to infrastructure unavailability, all earnings would be consumed. Unavailability could result in production delays or even outtakes. Moreover, competition pressures profit margins, making chemical parks potentially more attractive if they have access to cheap materials and energy feedstock on the global market (Bensassi et al., 2015).

2.3. Towards relocation implications

The literature on relocation decisions began with periodic reviews of relocation decisions (Ballou, 1968). Afterward, heuristics, limiting possible configurations and optimal multi-period solutions for limited numbers of alternatives, are derived under the heading of dynamic FLP (Sweeney and Tatham, 1976, Wesolowsky, 1973, Bastian and Volkmer, 1992, Hormozi and Khumawala, 1996).

2.3.1. Facility location planning and transport infrastructure

FLP is a major strategic management decision used to resolve location problems. FLP models often use mixed-integer programming techniques (see e.g. Daskin, 2011, Current et al., 2002, Church and ReVelle, 1974, Hakimi, 1964). Solutions that provide high service levels usually come with high costs, and vice versa (Nozick, 2001). FLP is predominantly used when companies evaluate one or more potential locations for new sites, but the literature on the connection between FLP and transport infrastructure is limited. Reliability in this context is usually concerned with the failure probabilities of facilities rather than transport infrastructure (Zhang et al., 2016, Farahani et al., 2009, Drezner, 2014).

Few studies have examined FLP in combination with aspects of transport infrastructure. Reflections on the locations of companies concerning transport infrastructure typically focus on patterns in the spatial distribution of companies and infrastructure (Button et al., 1995, Coetzee et al., 2017, McCalla et al., 2001, Shukla and Waddell, 1991). For example, Canbolat et al. (2007) use a framework of decision tree and multi-attribute utility theory (MAUT) to evaluate different countries as potential site locations. Hajibabai et al. (2014) consider the joint optimization of freight facility location and pavement infrastructure rehabilitation but focus on the particular case of road infrastructure and neglect the possibility of modal shifts and how infrastructure condition transmission can have a direct impact on user cost.

2.3.2. Location-Relocation Problem

Overall, the deterioration of infrastructure can have significant implications for location decisions, as disruptions to infrastructure can impair business activities for extended periods due to the long construction and maintenance periods and continuous demand. This is why this study focuses on relocation decisions that are not studied in the IW literature so far (cf. Caris et al., 2014).

Boloori Arabani and Farahani (2012) and Seyedhosseini et al. (2016) provide reviews on dynamic location problems, addressing the combined facility locationrelocation problem, as relocation is a common strategical decision of firms (Boloori Arabani and Farahani, 2012). 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.

Albeit, the literature does not explicitly include infrastructure availability in this list. Farahani et al. (2009) investigate a time-dependent single FLP and determine the optimal time to relocate. However, since they focus on distance measures toward demand points, they neglect congestion phenomena, infrastructure availability, or accessibility.

Relocation of headquarters provides implications on the welfare of workers (Fujita and Thisse, 2006) or on infrastructural needs such as improving airport facilities or lowering taxes (Strauss-Kahn and Vives, 2009). These works demonstrate the link between company decisions regarding relocation influenced by public authorities. Jiang et al. (2018), moreover, recognize interdependencies between transport accessibility and the probability of cities as relocation destinations but focus on industry-specific constraints.

De Bok (2009) suggest another method to evaluate facilities' relocation probability. They examine the influence of accessibility and agglomeration on the behavior 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:

$$P_{Relocate}(t) = \frac{1}{1 + e^{-u(t)}} \tag{2}$$

Where $u(t)$ is a utility function depending on the parameters above, both the utility and probability of relocating are time-dependent (De Bok, 2009).

2.4. Inland waterways and business locations

Infrastructure is seen as the essential location factor of business locations (Rezaei et al., 2018) and is a key driver of economic growth (Hong et al., 2011, Pradhan, 2019, Ahmed et al., 2021, Cigu et al., 2019). This is why 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). Bensassi et al. (2015) review logistics determinants in literature, while the Logistics Performance Index (LPI) provides an established metric considering available performance data based on empirical research related to ports, roads, rail, and air transport (see The World Bank, 2018). However, studies connecting water-borne infrastructure maintenance and economic performance are scarce (Feng et al., 2020, Wehrle et al., 2022a).

IWs 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 fees, and reduced number of accidents (Borodulina and Pantina, 2021, Gherghina et al., 2018). Like any other type of infrastructure, IW infrastructure requires investments above certain thresholds to contribute positively to economic growth through the provision of infrastructure service and performance (Hong et al., 2011). Therefore, IWs should be maintained efficiently to enhance the sustainable development of regional business locations dependent on IWT (Oztanriseven and Nachtmann, 2020). Literature on IW maintenance focuses on the civil engineering view instead of the economic impact of neglected maintenance. A summary of this is provided by Wehrle et al. (2022b). Nevertheless, literature on the effects of neglected infrastructure maintenance is scarce, focusing on road and/or railways (Chatti and Zaabar, 2012, Ke and Verma, 2021, Kwon et al., 2011, Stewart et al., 2011), while no literature is found with a focus on IWT.

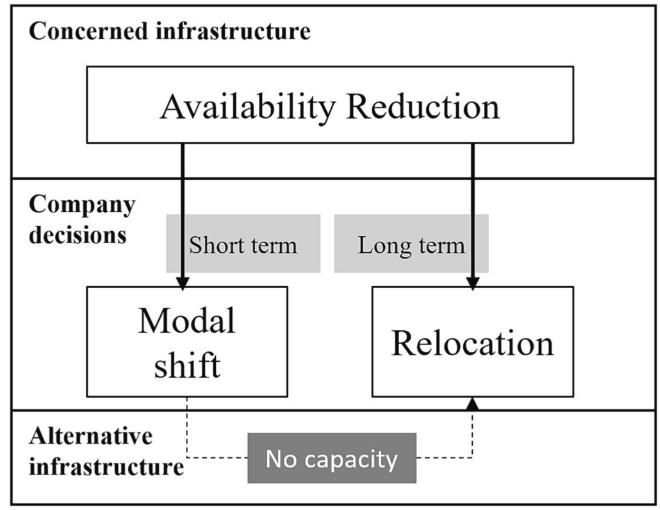

Fig. 2. Concept of research.

Despite these research gaps, IWs are now an increasing subject of research (Sys et al., 2020). Oztanriseven and Nachtmann (2020) propose an extensive model (MatTranS) to support informed IW 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. Overall, the literature lacks an applicable model to derive the impacts of infrastructure availability on operational and strategic business decisions, combining short-term and long-term economic consequences.

3. Research Methodology.

3.1. Concept

Fig. 2 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. Short-term reductions lead to modal shift decisions towards alternative modes, but 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 asset conditions due to a lack of maintenance resources directly impact the infrastructure network's availability. Therefore, the research question about the influence of infrastructure availability on company decisions is subdivided into 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 decreases in availability will trigger firm relocations?

To this end, a transport model (section 3.2) is considered to assess the cost increases incurred by a company due to the failure of infrastructure elements. Based on this, a relocation model (section 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. Meanwhile, the models enable the exploitation of public data, whereas companies can input their preferences. Infrastructure owners may integrate historical data or further expert knowledge. The model components are explained in detail in the following subsections.

3.2. Transport model

A transport model fulfilling the demand of IWT to analyze the impacts of infrastructure failure on transport cost answers the first subquestion *(How can cost increases resulting from unavailable infrastructure elements be assessed?)*.

Tavasszy et al. (2012) outline two relevant research avenues on freight transport demand modeling: 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 modeling 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) which 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 SCs between different SC agents like manufacturer, carrier, and customers has been, for example, is 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 assumed to be known but no supply origins (as is the case for the WGCN as case study), 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.

Accessibility points to the IW 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 into multimodal transportation and the impact on the choice of transportation mode by calculating the operational costs at an efficient match of supply and demand. Data is to be extracted from statistical data (e.g. Destatis, 2019, BMDV, 2016, cf., section 4.2). The relevant cost factors are taken from the "Federal Transport Route Plan 2030″ ("Bundesverkehrswegeplan 2030″) (BMDV, 2016) which is used to plan infrastructure projects based on their users' utility and welfare. The cost factors not only provide the same calculation basis used in public-decision making but are reviewed with business stakeholders for each revision of the Route Plan. Different scenarios are implemented based on real-world data which are aligned with the cases discussed (for a full documentation, please refer to Binsfeld, 2020).

The objective function (9) minimizes the total transportation costs, while the supply of goods by waterway transport and trucks is compared. The function derives the cost impact of ports not being accessible by IWT due to infrastructure failure and the extra cost of trucking to these ports to meet their demand. Accessibility points to the IW 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.

Table 1
Vehicle-related notations and description of transport model.

Notation	Description	Unit	IWT	Truck
$\alpha^{k,m}$	Vehicle related costs of transportation mode	[€/h]	x	x
$C^{k,m}$	Capacity of transportation mode k	[t]	x	x
$\beta^{k,m}$	Personnel costs per worker	[€/h]	x	x
$n^{k,m}$	Number of personnel depending on vehicle	–	x	
$d^{m}_{i,j}$	Distance between ports i and j using transportation mode	[km]	x	x
$q_{i,j}$	Number of locks between ports i and j	–	x	
h	Docking time at the ports	[h]	x	
τ	Lock time at the locks	[h]	x	
η	Handling performance	[t/h]	x	
$\mu^{k,m}$	Fuel costs depending of transportation mode	[€/km]	x	x
p	Port costs for inland waterways transportation while unloading	[€/t]	x	
$\epsilon^{k,m}$	Unloading costs at port	[€/t]	x	x
$\gamma^{k,m}$	Loading costs at other transportation mode	[€/t]		x
$s^{k,m}$	Speed of transportation mode	[km/h]	x	x

The formulas are as follows, according to Binsfeld (2020): Distance related costs (DC):

$$DC = \sum_i \sum_j \sum_k \sum_m \left(\alpha^{k,m} + \beta^{k,m} + n^{k,m}\right) \cdot \left(\frac{d^{k,m}_{i,j}}{s^{k,m}} + q_{i,j} \cdot \tau\right) \cdot x^{k,m}_{i,j} \tag{3}$$

Docking related costs (DoC):

$$DoC = \sum_i \sum_k \sum_m h \cdot \left(\alpha^{k,m} + \beta^{k,m} + n^{k,m}\right) \cdot y^{k,m}_i \tag{4}$$

Freight quantity related costs (FQC):

$$FQC = \sum_i \sum_j \sum_k \sum_m \frac{\alpha^{k,m} + \beta^{k,m} + n^{k,m}}{\eta} \cdot f^{k,m}_{i,j} \tag{5}$$

Fuel related costs (FuC):

$$FuC = \sum_i \sum_j \sum_k \sum_m \frac{d^{k,m}_{i,j}}{s^{k,m}} \cdot \mu^{k,m} \cdot x^{k,m}_{i,j} \tag{6}$$

Unloading related costs at the ports (PC):

$$PC = \sum_i \sum_k \sum_m \left(\phi + \epsilon^{k,m}\right) \cdot Q^{k,m}_i \tag{7}$$

Loading related costs from one transportation mode to the other (LC):

$$LC = \sum_i \sum_k \sum_m \gamma^{k,m} \cdot UQ^{k,m}_i \tag{8}$$

The above costs are aggregated to formulate the Total costs for IWT (TC) [EUR]:

$$TC = DC + DoC + FQC + FuC + PC + LC \tag{9}$$

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 1 provides an overview of all the variables used to 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:
(a) Cost model: Failure of an infrastructure element b on the route i,j increases transport costs by Δc_b
(b) 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 fulfill 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 enables deriving a stochastic availability considered in the formulation of risk scenarios Θ_i.

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 related costs of infrastructure unavailability. Moreover, the relocation model derives the firms' threshold of pain, the critical threshold for a decrease in availability that causes relocations (cf. section 2.2). In the context of the presented model, the threshold refers to Gast and Wehrle (2019) as the evaluating company defines its thresholds individually, while sector-specific tendencies or generalizations are possible.

The 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 companies derive from access to a functioning infrastructure and corresponding reductions in utility that result from a decrease in availability. Hence, the following steps are performed 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

$$P_R(A_s) = \min\{\max\{0; \Delta c_{s,\Theta i}(A_s) - c_R\}; 1\} \tag{10}$$

(1) Set k availability thresholds $A_{t1},\ldots,A_{tk}$ (determination of k potential critical threshold levels of availability $A_{t1},A_{t2},\ldots A_{tk}$, based on empirical data)
(2) 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):

$$P_R(u) = \frac{1}{1+e^{-u}} \tag{11}$$

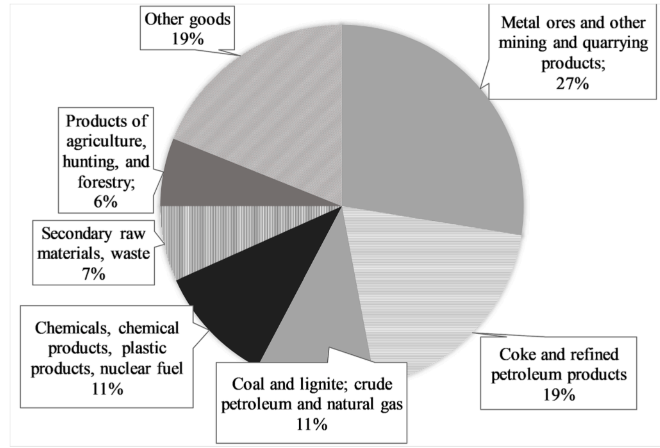

Fig. 3. Share of different types of goods in inland waterway transport in Germany (Destatis, 2019).

with

$$u = \beta \cdot A_s + (1-\beta) \cdot LPI + \alpha \tag{12}$$

with

$$\alpha, \beta \in [0; 1] \tag{13}$$

Referring to the first step and first sub-question, apply the concept of infrastructure availability as depicted in section 2.1.2 is applied. Thus, availability can be calculated via empirical data on failure times. The escalation parameter used to form the risk potentials represents a time parameter and a resilience factor. It thus includes the company's vulnerability in addition to the duration of the disruption. The factor represents revenue reductions and 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 Θ_{imax}.

The result primarily assesses the current situation, as the current availability is set in relation to the cost and utility function(s). Thereby, the model provides an answer to sub-question (2) and allows for 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." The interpretation is suggested to be done referring to (Gast and Wehrle, 2019), whereas the difference between current availability and the critical threshold is decisive.

Accordingly, the distinction between these values is crucial: while current availability reflects the maintenance status and thus the available capacity for shipping operations for logistics needs, the critical threshold specifies a minimum level of availability. The latter is required to be guaranteed in order to meet the requirements of shipping operations. Otherwise, i.e., if current (up to forecast) availability falls below this threshold, long-term relocations of logistics operations and thus of entire facilities become relevant.

The costs of unavailable infrastructure (sub-question 3) are assessed by combining the relocation and transport model, as the first step of the relocation model provides the calculation of scenario-specific escalated costs. The outcome of the combined 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.

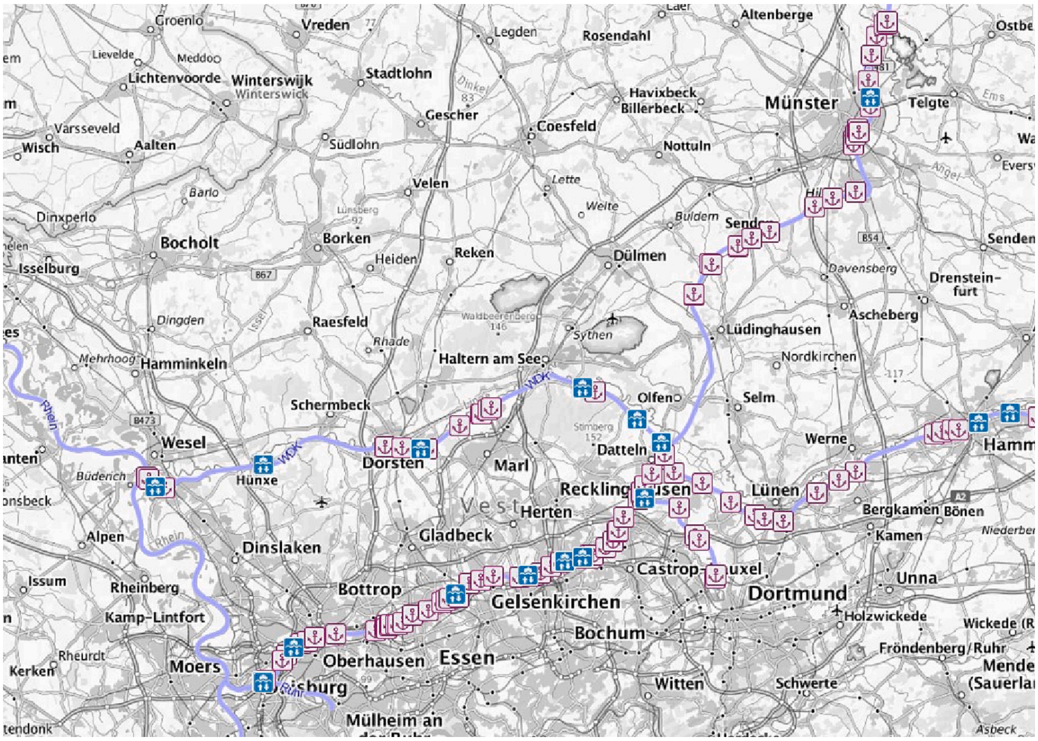

Fig. 4. West German Canal Network with depicted locks and ports. Geodata from Federal Agency for Cartography and Geodesy (2021), infrastructure elements according to of Transport and Infrastructure (2014).

4. Case

Due to the deteriorating infrastructure elements of German IWs and the chemical industry being heavily dependent on this infrastructure, the model focuses on the investment of public authorities' into infrastructure maintenance and the chemical industry as a key private stakeholder.

4.1. *West German Canal network*

Examining waterways as transport infrastructure, the (petro-) chemical industry with its foremost (liquid) bulk goods (van Hassel et al., 2018, Jetlund and Karimi, 2004) comes into focus. The industry has a direct share of 30% tonne-km on IWT in Germany (Fig. 3) making it a key stakeholder in the West German Canal Network (WGCN) located in Northrine-Westphalia (NRW). NRW is considered the most industrialized and populous region while having a share of more than half of waterway transportation in Germany due to the Rhine and canal network (Destatis, 2019).

Furthermore, the significance of the chemical industry can be demonstated as follow: Not only in terms of volume/weight are relatively many products and precursors from the chemical industry transported via the canal network, but also key products. Their global importance as for the worldwide automotive industry was demonstrated by the explosion of the CDT/acetylene plants, respectively, in 2013 and 2017 at the Marl Chemical Park (BurdaForward GmbH, 2013; Evonik Industries, 2017). Consequently, due to the high relevance of these primary products, other SCs (such as the automotive industry or mechanical engineering) are also indirectly affected in the event of a canal network failure.

The developed methodology is applied to the WGCN, illustrated in Fig. 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 ports are depicted with an anchor symbol, representing all varieties of ports from small to big, covered by (Destatis, 2019).

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 waterways in the case study area (Gast et al., 2020). In NRW, where the WGCN is located, waterway transport represents up to 30% of the modal split (Destatis, 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.

4.2. *Transport model*

The procedure described in section 3.2 is conducted as follows.

4.2.1. *Identify locations*

Locations of ports and infrastructure buildings are derived from available geodata as depicted in Fig. 4. Data on company locations are obtained from publicly available data. Routes of shipping are assessed based on the transport model that aims to satisfy port demand based on databases (Destatis, 2019) with the lowest cost (Binsfeld, 2020).

4.2.2. *Expected costs of route failure*

Expected costs of route failure are calculated based on scenarios of failed locks transferable to failures between two corresponding ports. The data is provided by statistical data (Destatis, 2019), and the federal ministry of transportation provides the cost factors and calculation (see BMDV, 2016). Different scenarios are implemented based on real-world data which are aligned with the cases discussed (for full documentation see Binsfeld, 2020).

Case (3), for instance, involves alternative failures of the direct

Table 2
Calculation of the case-based cost increases.

Scenario	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%	2.493%	249.275%
2	Gelsenkirchen	1.0869440	8.69%	88.63%	88.630%	11.370%	0.989%	0.989%	9.885%	98.854%
3	HerneOst	1.0047022	0.47%	80.99%	77.637%	22.363%	0.105%	0.105%	1.052%	10.516%
	WanneEickel	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%

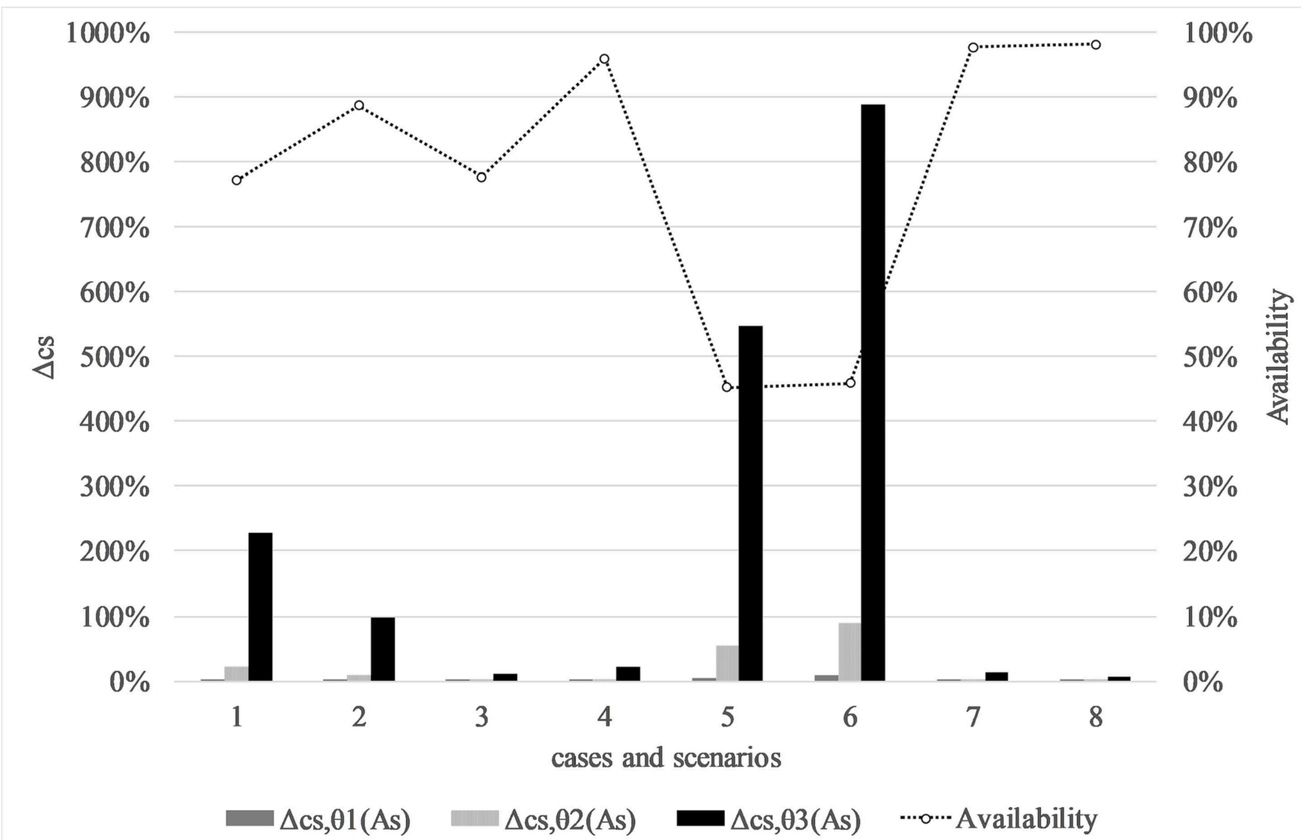

Fig. 5. Scenario-based cost increase and availability at the West German Canal Network.

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 2.

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 2). These percentages can already be compared with the discussion about thresholds of pain in section 2.2.

Table 3
Definition of escalation parameters.

	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

4.3. Relocation model

The procedure described in section 3.3 is conducted as follows.

4.3.1. Risk calculation

In addition to the results of the transport model, Table 2 shows the results of the risk calculation (Step 1) of the relocation model (see 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

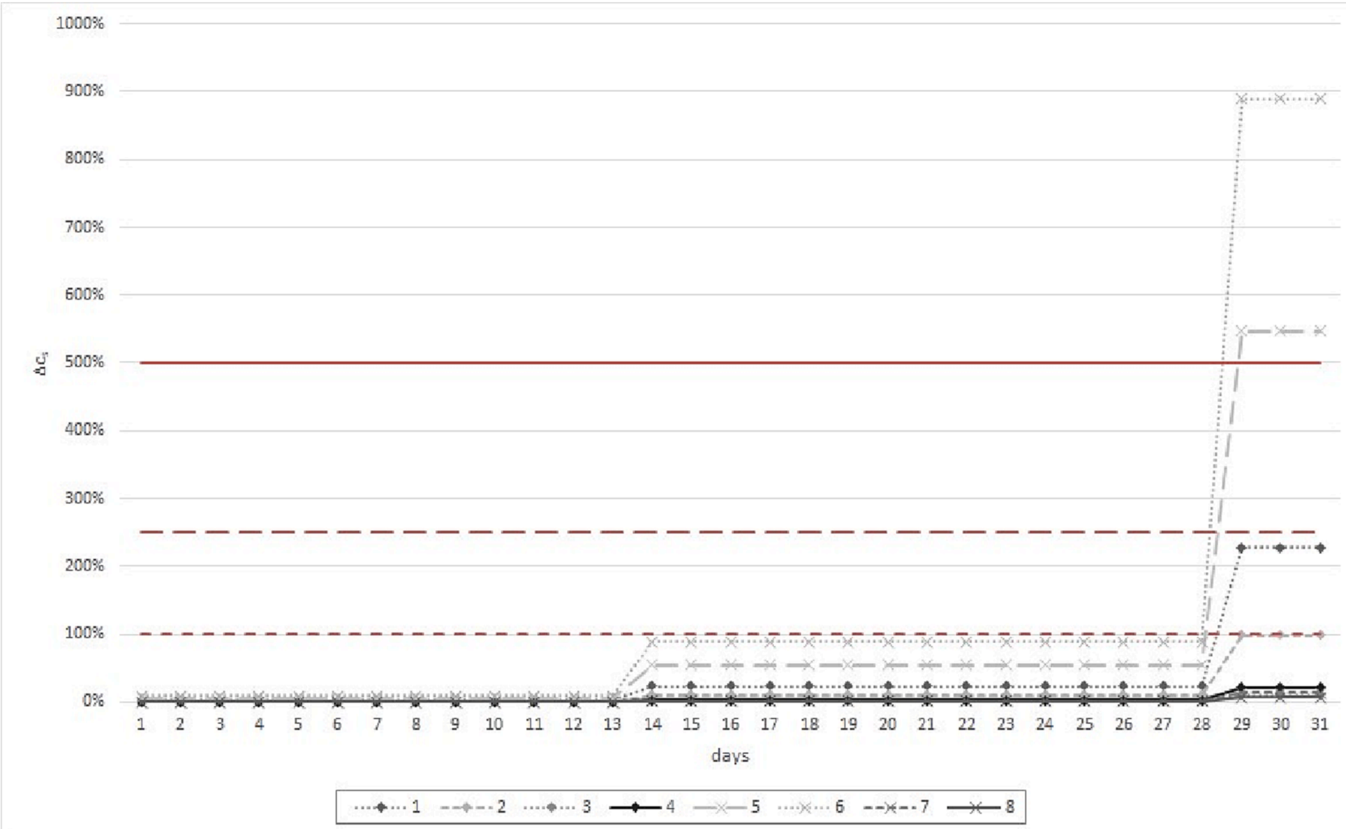

Fig. 6. Scenario-based cost increase over time at the West German Canal Network.

escalated costs $\Delta c_{s,\Theta i}$.

Fig. 5 illustrates the results of the transport model and the corresponding availabilities derived from the above-mentioned historical data. The escalating parameters Θ_i are set to $\Theta_i = 1,10,100$ and include the assumptions depicted in Table 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 lead to long-term considerations and even to business abandonment (according to Fig. 2).

4.3.2. Cost dependent probability to relocate

Next, the second step derives 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: $\Delta c_{R0} = 100\%$, $\Delta c_{R1} = 250\%$ and $\Delta c_{R2} = 500\%$. Fig. 6 illustrates for each scenario the cost increase over time from Table 2), showing in horizontal red lines Δc_{R0}, Δc_{R1} and $\Delta cR2$.

The interrelation between cost increase and infrastructure availability (Fig. 7) shows that a linear approximation within the respective risk potentials is roughly possible.

To calculate the probability to relocate, the authors use Fig. 8, revealing turning points in the formula of the calculated probability at

$$A_{\Theta,\Delta c_s, c_R}(u) = max\{\frac{100 \cdot \Delta c_s \cdot \Theta - 100 \cdot c_R - 50}{\Delta c_s \cdot \Theta}; 0\} \tag{14}$$

4.3.3. Availability thresholds

Then, critical thresholds of availability are set in the range of the identified turning points (Table 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:

$$A_t = \{50; 60; 70; 80; 85; 90; 95; 99; 100\} \tag{15}$$

These levels allow for further analyses of distributions of the current availability as a 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. Evidence for the analyzed thresholds can be found in the accompanying literature (Gast and Wehrle, 2019), while historical data about relocations to support empirical evidence is scarce and must be subject to future research.

4.3.4. Utility-based probability to relocate

These steps eventually derive the utility-based probability to relocate. The probability assumes a utility function depending on availability and LPI, whereby the latter is quantified by the value 4.2, having a maximum value of 5, which is normalized in the following. Expressions (10) and (11) yield a turning point of the utility-based function at

$$A_t = \frac{-\alpha + (1-\beta) \cdot \frac{LPI}{5}}{\beta} \tag{16}$$

Equating this with the identified threshold levels to determine the function parameters allows the applicant to parametrize the utility function, which reflects a company's benefits from transportation infrastructures. Fig. 9 shows the parametrization.

5. Results and discussion

Examining different critical thresholds concerning the considered cases makes it possible to analyze the overall condition of a system state of waterways and 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%).

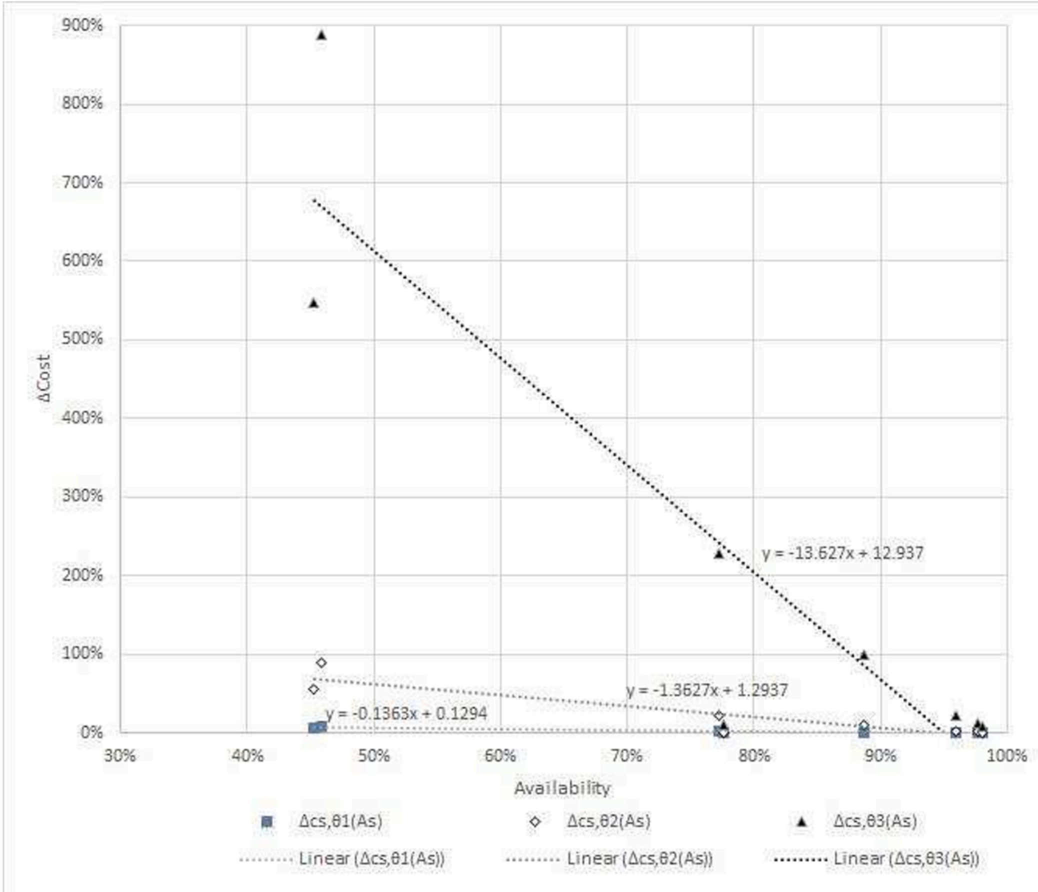

Fig. 7. Interrelation between cost increase and availability.

The more detailed comparison of the evaluated availability with the probability to relocate (Fig. 8) shows similar curves which differ in 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 (Fig. 8, bottom right, dashed) and the corresponding route show no (current) criticality since the current availability is comparatively high and the probability of relocation only becomes relevant once a significantly lower availability threshold is reached. Case 5 (Fig. 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 risk provoking relocation if the availability of the infrastructure is not increased, anticipating the scenario of lowest relocation costs (100%) in this case.

Case 6 (Fig. 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 of 77.20%. Meanwhile, case 3 shows no criticality potential since the low cost increase for unavailable infrastructure elements on the route is not decisive for the considered ranges of relocation costs.

A closer look at the results allows further conclusions to be drawn: If a hypothetical availability threshold is set at 50%, for example, 25% of the routes considered already prove to be critical. None of the routes reaches an availability of 99%. Compared to the derived critical thresholds, it becomes apparent that one out of eight routes lies below the acceptable risk. This is the route of the Wesel-Datteln Canal from the Wesel as the upper entrance to the WGCN to Marl. Accordingly, relocations would also be a realistic option for large chemical parks located there.

Assuming lower relocation costs, 37.5% of the routes are already below the respective individual critical threshold. These observations apply mainly to the highest escalation factor, i.e., a correspondingly high impairment of the waterway or high vulnerability of the industry.

Furthermore, the considerations from section 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.

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 and alternative routes. Comparing current and critical availability thresholds helps assess the urgency and potential of infrastructural measures and investments.

In detail, decision-makers can interpret the level of infrastructure availability for decision-making with this model. Furthermore, the proposed formulation allows decision-makers from the industry to optimize their relocation or investment choices based on the levels of infrastructure availability given by historical data and public investments. Moreover, other data from relevant industries, such as the coal or arc and stone industry, can be implemented to get insights into the optimal transportation mode choice. This analysis allows decision-makers to prioritize locks and bridges in maintenance which have the most decisive impact on costs in case of failure. To sum it up, the answer

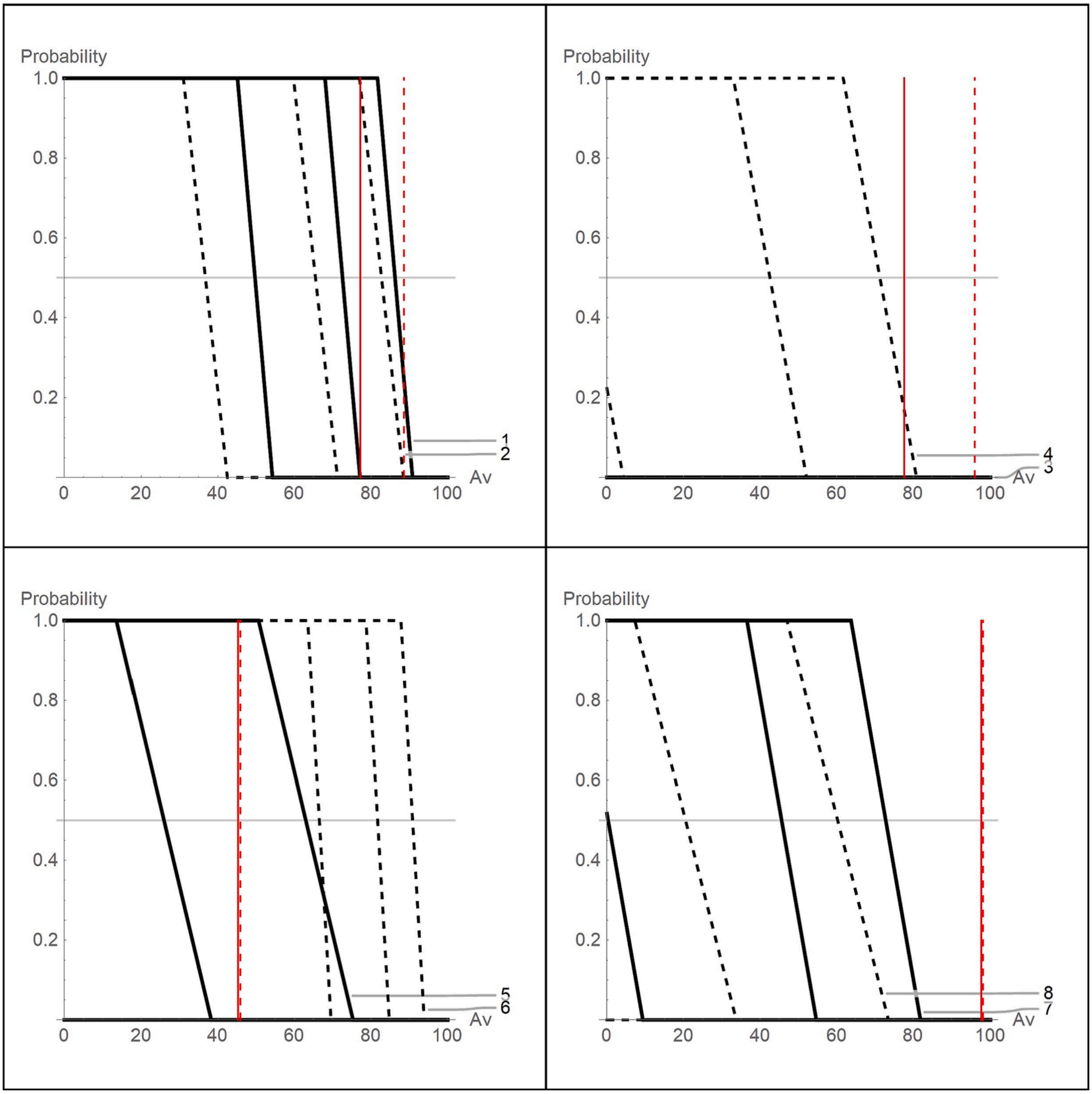

Fig. 8. Probability to relocate in dependency of infrastructure availability (av). each graph comprises two scenarios (1 line, 2 dashed, etc.) and the three considered levels of relocation costsΔc_R, whereas the most right (black) lines refer to the assumption of $\Delta c_R = 100\ \%\Delta c_s$. The red lines illustrate the respective current availabilities A_s, cf. Table 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Turning points of infrastructure availability, determining probability to relocate in accordance to equation (14).

		Θ_1			Θ_2			Θ_3		
scenario	**Cost**	$\Delta cR0$	$\Delta cR1$	$\Delta cR3$	$\Delta cR0$	$\Delta cR1$	$\Delta cR3$	$\Delta cR0$	$\Delta cR1$	$\Delta cR3$
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

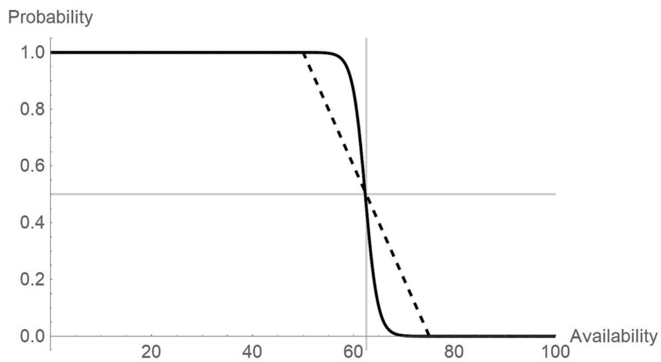

Fig. 9. Turning points of infrastructure, determining Probability of relocation as function of transport costs and aligned utility function for α = -50, β = 0.8, Θ = 2, Δc_s = 2, Δc_{R0} = 100%, revealing a turning point at A = 62.5, in accordance with case 5.

to the first research question (*How can cost increases resulting from unavailable infrastructure elements be assessed?*) is provided.

The relocation model enables the assessment of infrastructure availability at a particular point in time. Besides the calculation based on historical availabilities and route decisions, the model and its results imply that decreasing availability in particular should be investigated along well-defined cause-effect chains.. The study shows that a thorough understanding ft he 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 ft he infrastructure. Compared ft he underlying literature, the presented study provides the following insights: Availability as one ft he determining factors for relocation attractiveness (Gast and Wehrle, 2019) could be proven. Critical thresholds can be anticipated, as De Bok (2009) applies, and as this study transfers to infrastructure availability as a newly studied subject to determine the interplay of logistics operations, infrastructure and relocation decisions.

6. Conclusion

This study provides valuable insights into the relationship between infrastructure availability, short-term company reactions, and strategic options such as facility relocation by establishing a frequently overlooked link between risk-guided routing decisions on the one hand and infrastructure investment on the other. The derived availability thresholds have essential implications for infrastructure providers and policy makers responsible for maintaining and investing in transportation infrastructure. Thereby, the presented contribution extends the approach by Gast and Wehrle (2019). This way, the link between infrastructure maintenance and a region's attractiveness and competitiveness for industries is made transparent.

Moreover, the case study sets a focus on the highly relevant chamical industry with ist key products for several interconnected sectors and SCs (see section 4.1). VCI (2017) additionally illustrates the challenges faced by the industry, causing many strategic decisions to be reconsidered or taken anew (investments, orientation to customer groups, country focus). This supports the statements oft he presented contribution that there is a relatively high sensitivity, i.e. proximity ot he critical threshold, with regard to changes in risk factors. It becomes clear that the availability of waterways can be both a facilitator or an obstacle for this industry, depending on the evolution of the (set screws for) availability.

To conclude, this study provides instructive insights into the interconnections of infrastructure availability, short-term company reactions, and strategic options like relocating whole facilities. To answer the third research question, the *costs of infrastructure availability* are examined. Finally, the last research question (*Which decreases in availability will cause relocations* is addressed by demonstrating the relevance of infrastructure maintenance to enhance business locations and identifying critical availability thresholds. These thresholds can guide infrastructure providers and policymakers who need to know the"economically viable attractiveness" of their infrastructure assets. By extending the model of De Bok (2009), infrastructure availability becomes an operable factor in regional economic development. Notably, the presented case exhibits that several routes of the WGCN are yet critical, especially if relocation costs are low.

Further empirical studies have to be applied as this study is limited to using public data and assuming the preferences of private companies. Future research opportunities include confirming the critical thresholds through empirical surveys and examining the impact of railway infrastructure on the intermodal transport network. Furthermore, they could continue refining the proposed utility functions, e.g., by using empirical data about risk perceptions and relocation costs.

In light of the findings, this paper advocates for a more detailed analysis of infrastructure maintenance decisions, considering their overall economic impact on business locations.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data is attached as supplementary files, additional data ia availabe on request

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