Progress in Disaster Science 16 (2022) 100258

Contents lists available at ScienceDirect

Progress in Disaster Science

journal homepage: www.elsevier.com/locate/pdisas

A framework to evaluate systemic risks of inland waterway infrastructure

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ARTICLE INFO

Keywords:
Risk
Waterways
Empirical
Input-output-model
GIS

ABSTRACT

Purpose: This paper aims to enable the evaluation of systemic risks resulting from missing or misallocated repair measures of inland waterways infrastructure. In this context, cascading effects and risks arising from interdependent Critical Infrastructures (CIs) are of particular interest. The systemic risk assessment is implemented as a GIS-based tool 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. The results highlight critical buildings leading to potentially serious impacts on industry and population if the infrastructure elements are not maintained.
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 time-oriented to avoid potential damage and reduce impacts.
Originality: We examine the interconnected subsystems construction, industry and population in an aggregated risk framework to quantify risks stemming from complex infrastructure interdependencies with waterways as rarely explored infrastructure in this context. The implementation of a decision support tool for infrastructure operators as risk dashboard enables the integration of the approach into everyday infrastructure risk management.

1. Introduction

Infrastructure in all its varieties form the backbone of modern societies and constitute a complex System-of-Systems [1]. Transport infrastructure, as a prominent example, highlights the interconnectivities and interdependencies among infrastructure elements [2] and also the vulnerability against threats of all kinds which can lead to systemic and cascading risks [3]. 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.

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https://doi.org/10.1016/j.pdisas.2022.100258
Received 11 February 2022; Received in revised form 25 August 2022; Accepted 6 October 2022
Available online 7 October 2022

As a consequence, neglected or misallocated maintenance of deteriorating construction assets pose a threat to both business locations and to the population [4]. 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.

Nevertheless, the assessment of cascading failures which stem from neglected infrastructure maintenance of waterways cannot be found in the literature so far. This gap is mainly delimited by the research object of IWT with its unique vulnerabilities and threats caused by failure, as population and industry can be affected in various manners. Moreover, applications for decision-makers are lacking, which is why we want to address the corresponding spatial risk visualization in a scientific, yet user-friendly and comprehensive manner.

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 toward interdependent CIs in the following section. This brief review reflects literature on various CI systems, whereas we examine the suitability of methods for the application on waterways. 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 3.2. We consider the interdependencies of IWT damages toward connected CIs using Input-Output Models (section 3.3). Overall, our algorithm incorporates cascading risks in interconnected subsystems under consideration of ambiguity and goal prioritization of decision-makers. The developed methodology is applied to a case study in Germany in section 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.

2. Literature review

2.1. Risk assessment of transport infrastructure systems

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 [4,5], including hinterland transports [6]. Approximately 18 million tons of goods are transported on German waterways monthly [7], 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 [5]. 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 [4].

As mode of transport, IWT is seen as reliable when it is in normal operation [8]. 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 [8]. In 2015, for example, around 85% of locks, 73% of weirs and 87% of pumping stations were in an inadequate state of repair [9].

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 [2]. Referring sectors are depicted in Fig. 1, while the term CI requires a delimitation of the terms criticality and risk, which is done subsequently.

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 [11,12]. 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 [13]. The corresponding criticality, on the other hand, refers exclusively to the consequences of a system failure, independent of the probability of occurrence [14].

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 [15].

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 [2]. Interrelations between the focused sector “Transport and traffic” are highlighted in Fig. 1, according to [10] and the previous elaborations on IWT (section 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 (Fig. 1).

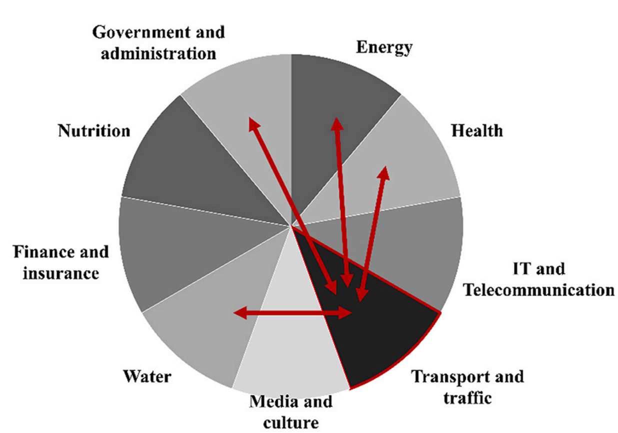

Fig. 1. Critical Infrastructures and interdependencies [10].

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 [16]. These challenges must therefore be addressed with interdisciplinary research and require a combination of different scales and units of measurement with regard to criticality.

[69] develop a cascading risk model but focus on the vulnerability and failure cascade within the system of dams, neglecting subsequent systems such as the population. [17] 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 formula (1) [17]. However, due to the simple multiplication of the factors, the analysis can result in misleading results. Such pure multiplicative calculations imply small resulting values. In addition, the choice of impact factors is crucial to the results and facing cascading risks.

$$CRF_i = Probability\ of\ occurrence{*}Vulnerability{*}Impact\ Factor \quad (1)$$

[18] 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 [18]. 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.

[19] 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 [19]. Hence, criticality is focused on industrial criticality if transferred to IWT.

Another attempt to assess criticality of transport infrastructure is provided by [20], 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 [21] or [22], 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 [4], 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.

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 Fig. 2). The following elaborations are adapted from [10].

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.

The risk process chain (Fig. 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 Fig. 2, these systems react to an event through the respective system-specific factors of vulnerability and criticality. Fig. 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.

2.2. Supply chain management and dependency on transport infrastructure

To assess threats arising from disrupted Supply Chains (SCs;

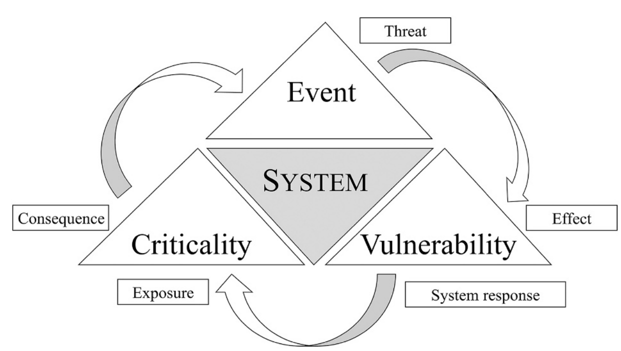

Fig. 2. Risk as process chain [10].

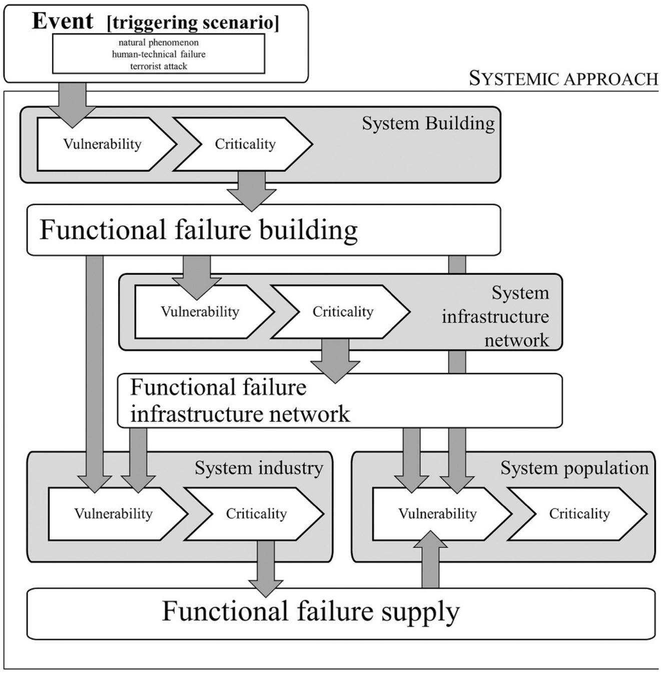

Fig. 3. Systematic risk assessment of IWT as System-of-systems.

subsystem *industry;* Fig. 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 toward disruptions.

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 [23], 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 [24]. [70], as one of the few approaches in literature, model interdependencies between IW ports and corresponding SCs: They consider the interdependency types geographic, service provision, and access for repair and assess ripple effects of disturbances via Bayesian networks,.

Companies may react by adapting their SC structure, choice of transportation routes and means [25], increasing SC visibility, enhancing buffer capacities or by considering the use of more generic input components [26–28]. 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. Moreover, for specific goods it is possible to become independent from public infrastructure, as via own pipelines [29]. However, for most industries and goods this is no feasible option, making relocation a possibility as well [30], since reliable transport infrastructures plays an important role in companies' location decisions [31,32].

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 [33,34], dynamic general equilibrium models [35], hierarchical holographic modeling [36], high-level architecture [37], and input-output models [38], among others [39]. 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 [1].

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 [40]. 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) [41] 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.

3. Research methodology

3.1. *Concept*

We derive a framework for measuring risks that operate at different, interconnected subsystems, based on [10], as described in section 2.1.4. The detailed concept and process of risk assessment is explained in section 3.2. Moreover, we use a supply-side IIOM to assess cascading effects of infrastructure failure on interdependent CIs in section 3.3.

3.2. *Framework*

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.

The risk assessment is based on the System-of-Systems depicted in Fig. 3, while Fig. 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 1). These functions are adopted from [42] according to [10], 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

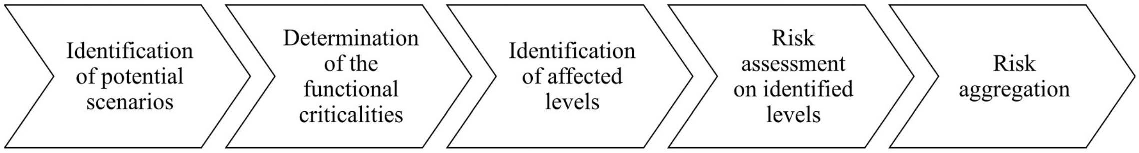

Fig. 4. Procedure of risk assessment.

Table 1
Interdependencies of functions.

Function of building	Function of network: water-retaining	Function of network: traffic-relevant
water-retaining (wr)	X	X
water level regulating (wlr)	X	X
traffic-relevant (tr)		X
securing (s)	X	X
transversal (t)	X	X

relevance".

This chaining logic from Table 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 (Fig. 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 [10]. [43,44,71] provide detailed literature about the assessment of building vulnerability, while details about the assessements within the subsystem population can be found in [45]. In general, the methodologies of the subsystems *industry* and *population* incorporate the assessment of the consequences in the event of a damage. These include alternative routes and modal shifts, warning times, topography, and population exposure, among others.

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 (Fig. 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.

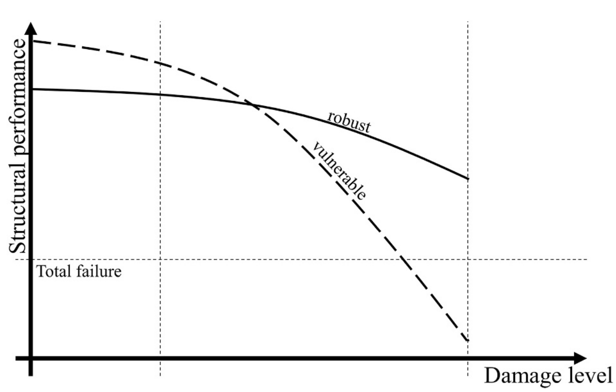

Fig. 5. Damage sensitivity for vulnerable and robust structures. [43].

3.2.2. Risk assessment

The aggregation toward a consistent risk assessment is conducted via s scenarios per building b, considering each of the identified relevant subsystems (Step 3, Fig. 4), according to the following formula based on Hodges-Lehmann [46,47]:

$$Risk_b = \alpha^* \sum_s u_{bs} p_{bs} + (1-\alpha)^* \max_s \{u_{bs}\} \tag{2}$$

The expression incorporates the stakeholder's disutility u_{bs}, which reflects the risks for industry and population. While the left term of expression (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 α, $\beta \in [0;1]$ can be determined by the decision maker: $\alpha = 1$ (decision maker is an expected utility maximizer with a neutral attitude toward 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):

$$u_{b,s} = \beta^* Risk_{Industry,b,s} + (1-\beta)^* Risk_{Population,b,s} \tag{3}$$

Furthermore, a scenario-specific, structure-immanent vulnerability of the construction structure $p_{b,\,s}$ as approximation of the probability of occurrence is normalized and included:

$$p_{b,s} = \frac{Vulnerability_{b,s}}{V_{max}{}^* s_{max,b}} \tag{4}$$

The values for vulnerability and risk are determined in the value range [0;5], resulting in $V_{max} = 5$. The proposed methodology overcomes the problem of rippling effects leading to small probabilities of occurrence due to a long chain and the oftentimes multiplicative characteristic of risk calculations, as shown by eq. (1). The weighted formulation enables the consideration of worst-case scenarios (α) and the goal prioritization allows both the incorporation of vulnerability and criticality in the respective sub-systems in an independent manner. Hence, and by incorporating the vulnerability rather than pure probability of occurrence, our methodology is hardly susceptible to the problem of cascading decreasing probabilities of occurrence.

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).

3.3. Risk for interdependent CI

The IIOM (cf. section 2.2.2) provides a method to assess the impact of a failure in one CI toward 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.

3.3.1. Input-output model

The flows of goods in an economy can be represented by the Gozintograph in Fig. 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 [40] is given by eq. (5), briefly modified to eq. (6), showing that production and consumption are linearly related by $[I-A]^{-1}$ and that a change in final demand influences the total production. Hereby, A is the technical coefficient matrix, 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.

$$x_i = \sum_{j=1}^{n} a_{ij}x_j + c_i \tag{5}$$

$$X = [I-A]^{-1} \times C \tag{6}$$

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 connected to demand-side disruptions [50]. A more relevant variation for our case is the supply-side IIOM, which allows to assess disruptions in supply. The calculation of the supply inoperability p is represented by eq. (7) where $z^{'}$ is a supply disturbance vector and $A^{s^{'}}$ is the supply interdependence matrix, according to [51], which can be extracted from an IO table using eq. (8) and (9).

$$p = (I - A^{s^{'}})^{-1} * z^{'} \tag{7}$$

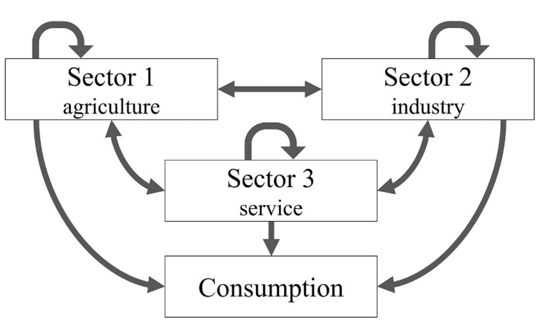

Fig. 6. Flows of goods as basis for IOM, cf. [48]; [49].

$$z^{'} = (diag(\widehat{x}))^{-1} * (\widetilde{z} - \widehat{z}) \tag{8}$$

$$A^{s^{'}} = (diag(\widehat{x}))^{-1} * A^{s} * diag(\widehat{x}) \tag{9}$$

The supply disturbance vector z' is calculated by multiplying a diagonal inverted matrix of the planned production $\widehat{x}$ with the difference between the planned offers $\widetilde{z}$ and the reduced offers $\widehat{z}$. The supply interdependence matrix $A^{s^{'}}$ is calculated using the supply-side coefficient Matrix A^{s} and $\widehat{x}$. With these results the supply inoperability p can be calculated, considering the CI sectors depicted in Fig. 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?*.

4. Case

4.1. West German Canal Network

We apply our methodology to the area of the West German Canal Network, consisting of 350 km of canals connecting the Ruhr area and the German North Sea ports [52]. Table 2 shows all object groups of the considered IWT infrastructure [42]. 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 4 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 [53]. Moreover, the region of North Rhine-Westphalia (NRW) is characterized by a comparatively high population density and a significant economic importance, which was mainly backed by the coal mines and steel industry.

4.2. Framework

As stated in section 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

Table 2
Object types West German canal network [10,42].

	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 levelers, pipe dock levelers
600	Objects for other direct tasks	Protection facilities against dilution damage Extraction and inflow structures Hydroelectric power plants, Fish passes

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.

4.2.1. Risk assessment

4.2.1.1. Identification of potential scenarios. 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 3.

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.

4.2.1.2. Determination of the functional criticalities and affected subsystems. As outlined in section 3.2.1, potential functional failures are derived first for the subsystem *building* (Table 3, 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 4 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 [42].

Table 3
Risk concept for the subsystem 'building', cf. [10].

	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 flow-through**
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

4.2.1.3. 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.

4.2.2. Risk aggregation

The details of the risk aggregation for an exemplary building is shown in Table 5. Based on the previously identified scenarios and the collected data among the described steps, we apply formulas from section 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.

Specific data originates from assessments of building vulnerability ($Vuln._{b,\ s}$), civil protection ($Risk_{Pop.,\ b,\ s}$), and empirical research for the acquisition of data for $Risk_{Ind.,\ b,\ s}$ as economic risk potential, which is not described here in further detail.

4.2.3. GIS application and risk dashboard

4.2.3.1. User interface. Risk assessment and aggregation is performed for each building in the modeling 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 Fig. 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.

By selecting a specific building, the user obtains more information about the building and its risk assessment, as Fig. 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 (Fig. 8, bottom left) as well as to a pop-up of the listing of possible resilience-enhancing measures (Fig. 8, top right). In addition, the average vulnerability across the scenarios is presented, for which again a scenario-specific explanation is available (Fig. 8, bottom right). The overall risk is visualized by color next to the total risk value.

Fig. 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 (Fig. 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.

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

Table 4
Functional criticalities of objects. Subsystems building and network.

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	x		x			x	x	x	x
112	Canal bridges	8	x		x			x	x	x	x
213	Weirs	2	x	x	x			x	x	x	x
221	Feed pumping station facilities	18		x	x				x		x
232	Flood barrier gate systems	1	x			x		x	x	x	x
233	Safety barrier gate	17	x			x		x	x	x	x
311	Ship lock facilities	17	x		x			x	x	x	x
510	Bridges	276					x		x		x
535	Culverts	168	x				x	x	x	x	x
537	Siphon (Düker)	238	x				x	x	x	x	x

Table 5
Calculation of risk for building b: ship lock Gelsenkirchen; south chamber.

Scenario	$Vuln._{b,s}$	$p_{b,s}$	$Risk_{Pop.,b,s}$	$Risk_{Ind.,b,s}$	$u_{b,s}$	$u_{b,s} \times p_{b,s}$	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		

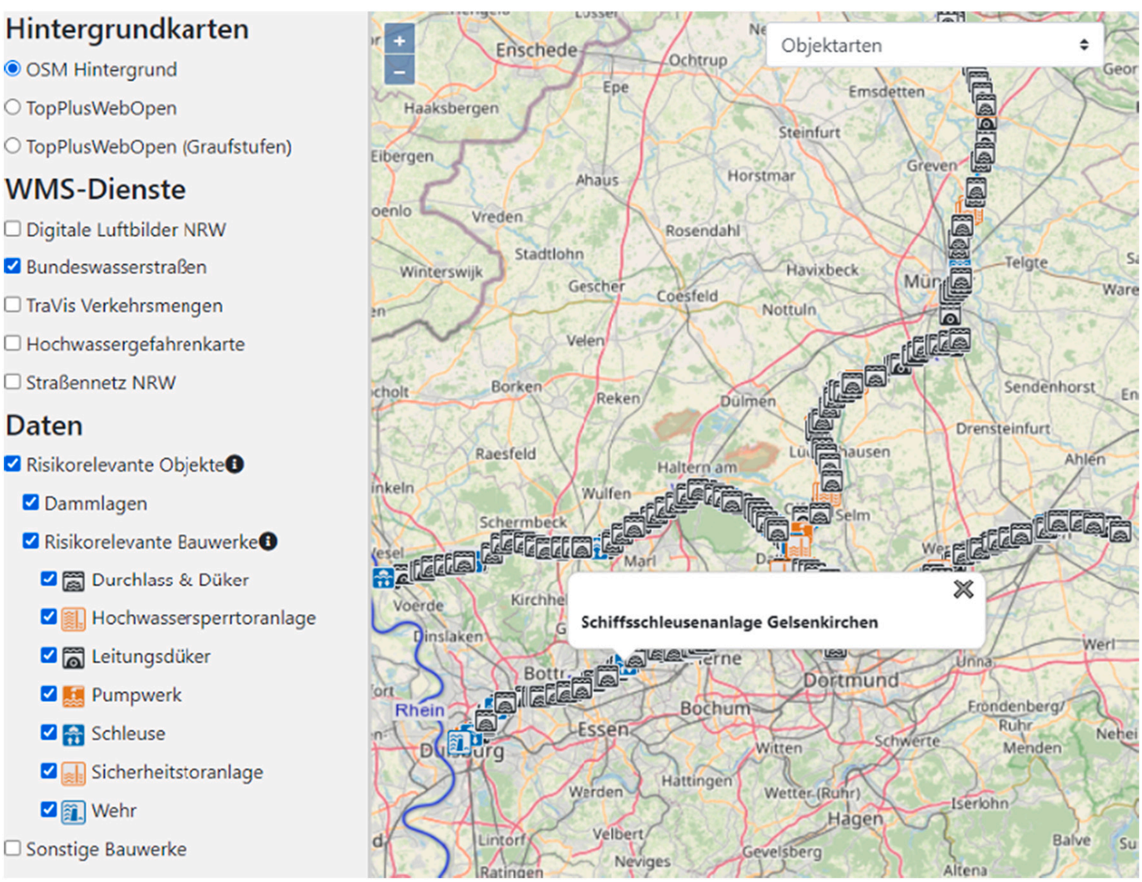

Fig. 7. Tool overview.

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.

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 3.3.

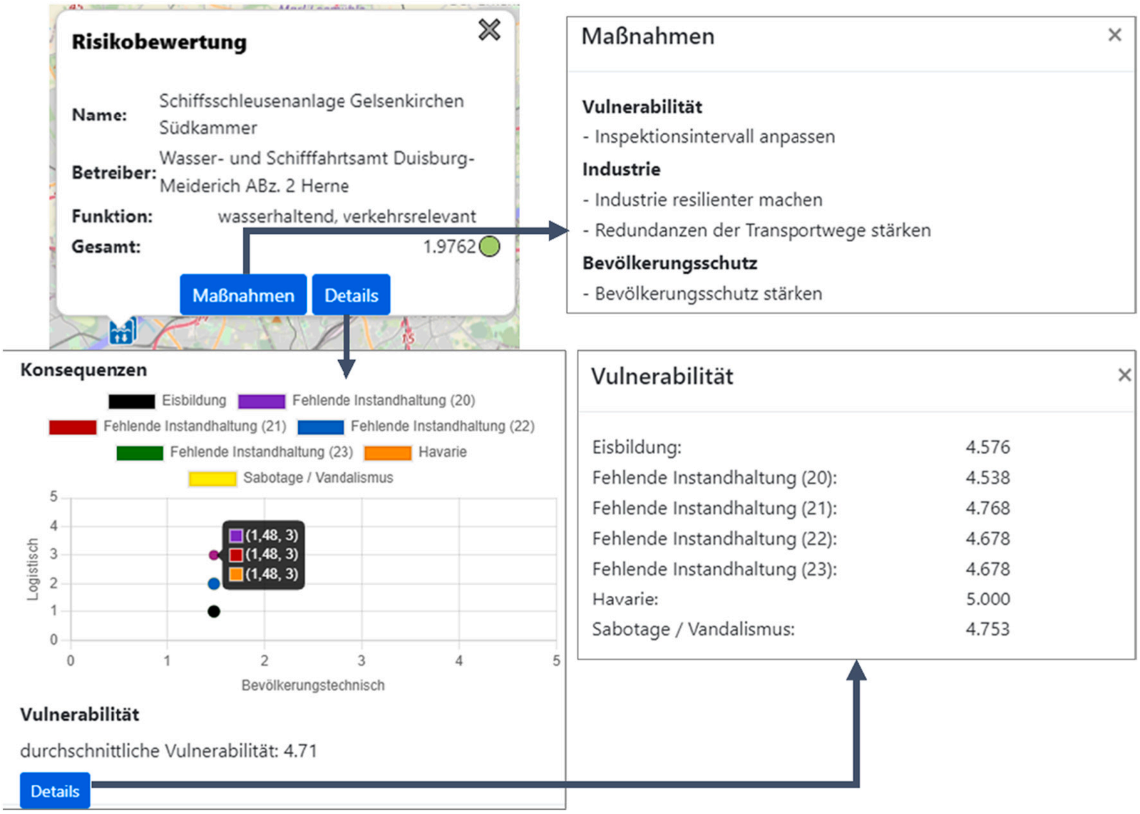

Fig. 8. Illustration of risk assessment in GIS-Tool.

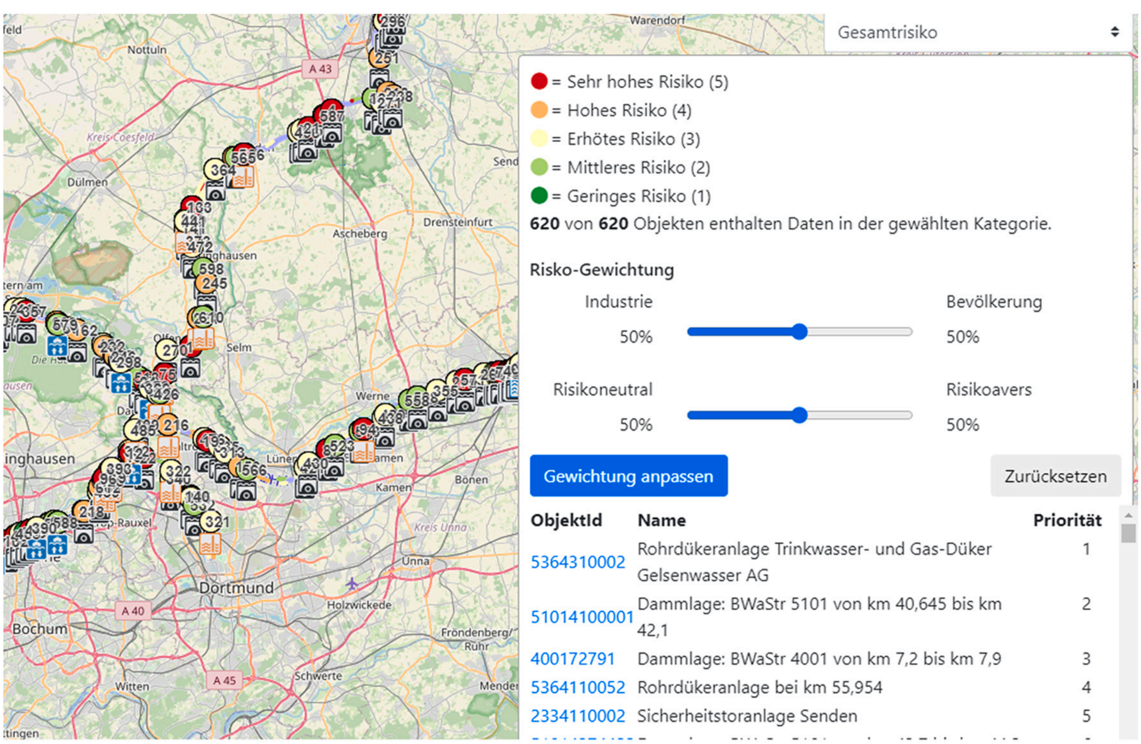

Fig. 9. Layers and prioritizing.

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 [54].

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 6 showing the shares of most significant commodity groups of IWT.

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 7.

4.3.1.2. Power supply. NRW produces 30% of Germany's electricity and re-consumes about 40% of Germany's industrial electricity [57], 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 (Fig. 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 by the German government [58]. Nevertheless, major sources of power generation are still dependent on coal and gas (Fig. 10).

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 [60].

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%) [61].

Thereby, the amount of cooling water in Germany has already been reduced by 30% from 2013 to 2010, due to the energy transition [62]. 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 4.3).

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 [55].

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 Fig. 11. For the corresponding sectors we carried out the IOM/IIOM analysis as described in section 3.3.

Table 6
Total IWT by freight division in NRW in January 2020, cf. [55].

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 7
Origins of public water supply in Germany, cf. [56].

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%

4.3.2. Input-output-model

We use the IIOM the to analyze supply-side shocks of IWT toward the sectors of water and energy supply. Thereby, the Input-Output Table (IOT) of 2017 (Revision 2019; [63]) does not sufficiently account for regional differences, which is why we use regional IOTs for the supply-side IIOM that shows the relationships between 16 sectors, illustrated by Fig. 12 [64]. Those include "electricity, gas and water supply" (sector E) and transport, storage and communication (sector I), as shown by Table 8.

We consider supply-shock levels to depict damage to waterway infrastructure. Two cases are distinguished: (1) a supply shock of 10% and (2) 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 4.2.1). Therefore, eq. (8) leads to maximal inoperability, if eq. (10) applies for commodity group i:

$$z_i^* = \frac{\widetilde{z_i}}{\widehat{x_i}} \tag{10}$$

Moreover, the impact of a maximum disruption in the transportation sector on the supply sector is calculated according to expression (10) from the planned supply in the transportation sector and the planned total production to a supply shock level. 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:

To conclude from sector I to IWT, we assume IWT's share of all freight transport services in NRW of 12% [65]. In addition, we determine the share of canal-based freight transport by IWT of the shipping transport volume in NRW to 60% [53]. Thus, 7.2% of the value added in Sector I is attributable to IWT in NRW.

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%. Fig. 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,

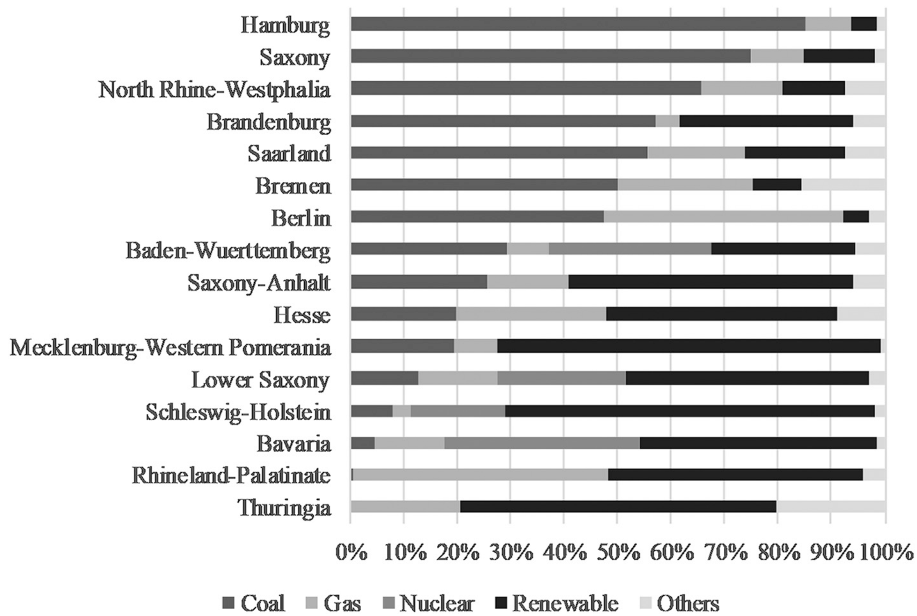

Fig. 10. Types and shares of power generation in Germany, 2017cf. [59].

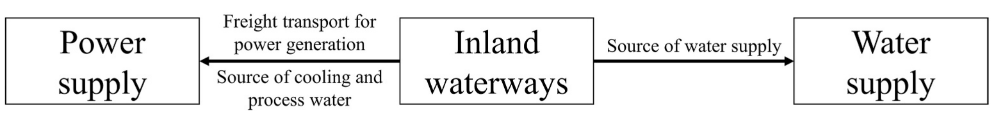

Fig. 11. Interdependencies of IWT and water and power supply.

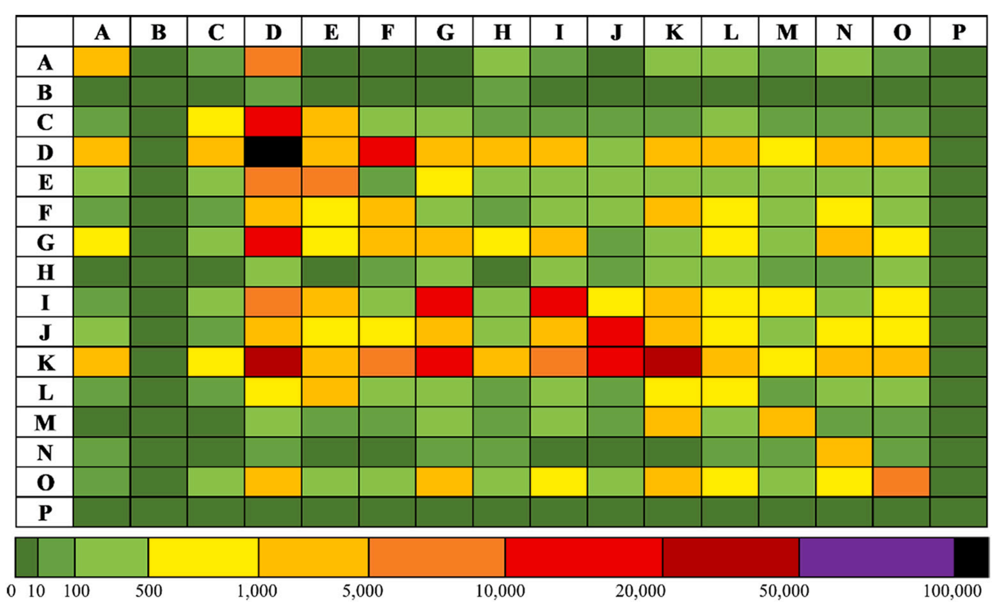

Fig. 12. Regional Input-Output Matrix according to [64], values in mio EUR; Illustration adapted from [72].

whereas, the “Electricity, gas and water supply” sector has an inoperability of only 1.31%.

Moreover, Table 9 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.

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.

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

Table 8
Sectors of regional IO-Table [64].

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

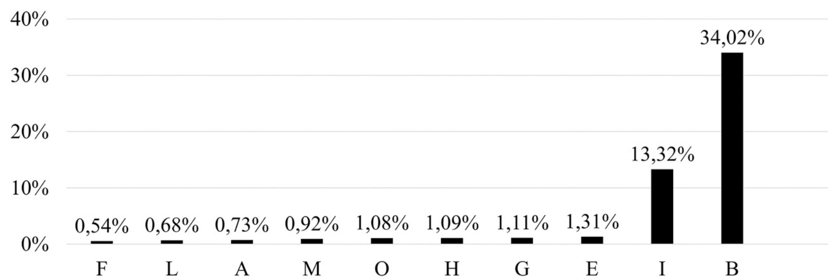

Fig. 13. Impact of 10% inoperability in sector I, in percentages.

Table 9
Inoperability of sector E resulting from supply restriction of canals.

	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%

potentially affected industries. We integrated the application of input-output modeling 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.

We demonstrate the necessity of focusing on supply-side shocks rather than considering demand-side shocks only. Applying the supply-side IIOM implies shocks in the supply and thus the provision of infrastructure as public good. 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. A risk-based maintenance strategy has proven to be necessary, as multiple risks propagating through the system face scarce maintenance resources. 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.

Innovation points are provided by promoting risk as process chain with its criticality being dependent on functional criteria which is rather easy to delimit. We analyze the infrastructure as System-of-Systems and provide a quantitative framework to incorporate both risk aversion and goal prioritization into risk assessment. This is innovative foremost under consideration of IWT infrastructure with its unique characteristics.

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. Moreover, future work must incorporate uncertainty analyses to provide more robust results, as we now focus on providing a holistic and applicable framework. Thereby, following research may sets focus on effects of population, production suspension loss, and recovery time. The keyword "loss" then points to the possibility of measuring risk in all its determining parameters in monetary units – therefore, e.g., the results of the IIOM can be used and be transferred into loss curves. [66–68] may support the quantification within the sub-systems.

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.

CRediT authorship contribution statement

Rebecca Wehrle: Conceptualization, Methodology, Data curation, Investigation, Writing – original draft. **Marcus Wiens:** Supervision, Methodology, Validation, Writing – original draft. **Frank Schultmann:** Supervision, Writing – review & editing, Resources.

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.

Acknowledgements

The authors want to thank the partners in the joint research project PREVIEW. The project is funded by the security research program (www.sifo.de) of the German Federal Ministry of Education and Research (BMBF) via grant number 13N14697. We acknowledge support by the KIT-Publication Fund of the Karlsruhe Institute of Technology. Special thanks go to Fabian Neff, Alexander Tolle and Chenghao Xu.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pdisas.2022.100258.

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