A systemic risk framework to improve the resilience of port and supply-chain networks to natural hazards

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Abstract Ports are embedded in different networks, including the local critical infrastructure network, the regional hinterland transport network, and the global maritime transport network. These networks are exposed to a variety of natural hazards causing disruptions that can propagate to other network components, resulting in wider supply-chain losses. However, the risks of such indirect network disruptions, or systemic risks, are often not considered in risk analysis of ports. We propose a systemic risk framework for different networks interconnected through ports, and describe the state-of-the-art risk modelling approaches to quantify systemic risks. In addition, we present a port risk layering framework that can help identify how resilience against systemic risks can be improved. As climate change will likely increase the occurrence of natural hazards to ports and transport networks, efforts to enhance system-wide resilience should be considered, alongside port adaptation, to prevent supply-chain losses to exacerbate in the future.

Keywords: Systemic risks; Natural hazards; Resilience; Maritime transport; Supply-chains.

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Introduction

Ports are critical nodes in international trade and global supply-chain networks (Becker *et al.*, 2013, 2018; Ng *et al.*, 2015). Every dollar of trade flowing through a port will directly or indirectly generate an additional 4 dollars of global industry output (Verschuur, Koks and Hall, 2021). Apart from their trade facilitation function, ports often serve as important hubs of industry clusters and other critical infrastructure networks, such as road and rail transport, electricity generation, and waste disposal. Given their strategic location along rivers and coastlines, ports are often exposed to a variety of natural hazards such as earthquakes, tropical cyclones, storm surges and river flooding (Ng *et al.*, 2015; Verschuur, Koks and Hall, 2020; Izaguirre *et al.*, 2021). The high density of critical infrastructure networks, and industry in close proximity to port areas, can result in large economic impacts in the case of extreme natural hazards. In many instances these impacts materialise as direct damage losses to physical asset stocks located within the port boundaries. For instance, Hurricane Katrina (2005) caused a total of $US 1.7 billion in direct damages to South Louisiana ports (Santella, Steinberg and Sengul, 2010), while the direct damages to Texas ports as a result of Hurricane Ike (2008) were estimated to be US$ 2.4 billion (FEMA, 2008).

Beyond their boundaries, ports are embedded within local critical infrastructure networks, regional hinterland transport networks and global maritime transport networks. The collection of these networks is hereafter called *port networks*. The direct damage losses to the physical assets are only part of the economic losses associated with ports. Because of the interconnectivity of the different networks, local events may trigger potential knock-on effects to other network components (Buldyrev *et al.*, 2010; Levermann, 2014). This type of risk, often called systemic risk, captures the "propensity for cascades of secondary failures to be triggered by individual events" (Hochrainer-Stigler *et al.*, 2020). This implies that port disruptions due to hazards (natural and man-made) further propagate to other networks, leading to indirect economic losses due to trade and supply chain disruptions. For instance, damages from Hurricane Katrina in 2005 led to almost US$ 900 million in agricultural trade losses due to transport disruptions (Trepte and Rice, 2014), and Typhoon Maemi (2003) left the Port of Busan inoperable for 91 days, and it caused severe disruptions to global maritime trade and supply-chains (Lam, Liu and Gou, 2017). Disruptions to any of the network components that link to ports (e.g., transport network) can also affect port operations and disrupt supply chains. For example, in 2017, flooding of a railway network that connect Australian coal mines to the port of Hay Point resulted in 45 days of reduced operations (Verschuur, Koks and Hall, 2020), causing bottlenecks in Chinese and Indian steel mills (Lenzen *et al.*, 2019).

Past research has shown that the indirect economic losses due to port disruptions can be as large, or even larger, than the direct damage losses to infrastructure (Koks and Thissen, 2016). Given that global trade and supply-chain networks are becoming increasingly interconnected (e.g.(Maluck and Donner, 2015) and the occurrence of climate-related extreme events may increase in frequency and severity due to climate change (Hallegatte *et al.*, 2013; Izaguirre *et al.*, 2021), systemic risks to port networks need to be analysed and quantified. Including such systemic risks in risk analysis frameworks not only allows quantifying how different actors in the interconnected port networks are exposed to such risks, but it also helps identifying ways to improve the resilience of the port networks. Solutions to improve network resilience often combine interventions to reduce the asset damages (e.g., elevating ports or making roads climate-proof) with approaches to reduce the risk of systemic impacts (e.g., rerouting, mode substitution, import substitution) (Hochrainer-Stigler *et al.*, 2020; Pant *et al.*, 2020).

Over the years, several port and maritime resilience frameworks have been constructed (Mansouri, Nilchiani and Mostashari, 2010; Berle, Rice Jr. and Asbjørnslett, 2011; Omer *et al.*, 2012; Wendler-Bosco and Nicholson, 2019). However, many of these frameworks do not account for systemic risks, and therefore also fail to present ways that port network resilience can be quantified and improved. On top of that, a large body of research has focused on quantifying risk to port assets, either through detailed case studies of port disruptions (Rose and Wei, 2013; Pant *et al.*, 2014; Zhang and Lam, 2015; Pitilakis *et al.*, 2019; Zhang *et al.*, 2020), or large-scale risks to port operations (Christodoulou, Christidis and Demirel, 2019; Izaguirre *et al.*, 2021). Still, analytical risk frameworks looking at systemic risk across systems and scales of port networks are less well established.

To bridge this gap, this paper discusses the various networks ports are embedded in, it identifies the systemic risks that these networks face, and how these can affect port operations and ultimately lead to supply-chain losses. We particularly focus on weather and climate related extreme events, as these affect such networks frequently (Verschuur, Koks and Hall, 2020; Izaguirre *et al.*, 2021) and because of the significant challenges ports, and supply-chains as a whole, face in adapting to a changing climate in the future (Becker *et al.*, 2013, 2018; Levermann, 2014; Ng *et al.*, 2015). We start by presenting a systemic risk framework that illustrates the multi-scale nature of port networks. Afterwards, we discuss three networks (i.e., critical infrastructure network, the hinterland transport network and the maritime transport network) that form the overarching port network, covering the scale and network characteristics, as well as the systemic risk studies that have been undertaken. We further discuss how failures in these networks can ultimately cause economic spillover effects to supply-chains and, finally, we present a 'port risk layering' framework that allows identifying various resilience options to reduce economic losses. We conclude with a set of recommendations for future research on systemic risks in port networks.

A multi-scale port network representation

Networks are characterized as collections of nodes and their connecting edges. We consider ports as important nodes in multi-scale hierarchical networks, governed by spatial extent and economic linkages, which have different subnetworks that interact with each other, as shown in Figure 1. At the top of the hierarchy, the maritime transport network can be schematised as ports (nodes) and global transportation routes (edges) (Figure 1a). The hinterland transport network (Figure 1b) covers the transportation networks (road, rail, inland water transport) that are used to supply commodities from the port to the production or demand centres (or vice versa) at regional scales. Lowest in the hierarchy, the critical infrastructure networks consist of the port assets and the critical infrastructure assets they depend on (e.g., electricity transmission and generation, telecommunications, water). These critical infrastructure networks are often local (Figure 1c), with the critical infrastructure assets located either within the port domain, or within a close proximity to the port. The supply-chain networks depend upon these different physical networks and their resilience determines the extent to which supply-chains will be disrupted. On a global level, the maritime transport network supports international trade flows that connect supply-chains in different countries, whereas the hinterland network supports trade at the regional scale by facilitating freight flows from and to the port. Locally, firms may depend on ports for the storage of goods, or have industrial facilities integrated within the port domain (e.g., petrochemical facilities in the port of Rotterdam).

Climate-related risks can disrupt individual nodes and edges in the different network layers of Figure 1 and thereby directly or indirectly affect operations, resulting in economic losses. In traditional risk analysis, risk is often defined and expressed in terms of asset damage, or direct physical stock losses. Risk is the combination of the possible probabilistic hazard scenarios (i.e., the likelihood and severity of a hazardous event), the exposure (i.e., the inventories of assets exposed to this hazard), and vulnerability (i.e., how does the hazard lead to damage or failure) of assets (Meyer *et al.,* 2013). Such traditional risk analysis ignores the potential network effects of asset failure (e.g., how failure in one node can affect another node), thereby failing to include the indirect failure pathways of nodes, and the port as a whole. In order to understand and quantify such systemic risks, the aforementioned risk framework needs to be expanded with a representation of the networks; i.e., the way nodes and edges are interconnected and how they are used. For instance, for the hinterland transport network of a port, this would mean adding information on the physical infrastructure networks that connect ports to the hinterland and the freight flows that use certain transport links. On top of that, one needs to characterise whether or not the network can buffer disruptions. The resilience of the networks then refers to their ability to absorb failures and quickly recover if failure occurs, thereby minimizing the losses to the end-users of the networks (e.g. firms) (Pant *et al.*, 2020).

In terms of supply-chain losses, a number of studies have estimated potential macro-economic losses due to local port disruptions, using input-output analysis in combination with disaster impact models (Park *et al.*, 2008; Rose and Wei, 2013; Pant, Barker and Landers, 2015; Koks and Thissen, 2016; Thekdi and Santos, 2016; Rose, Wei and Paul, 2018). These models simulate the wider output losses as a result of a trade bottleneck caused by a port disruption. For instance, Rose and Wei (2013) estimate that a 90-day disruption to the ports of Arthur and Beaumont (United States) can cost up to US$ 167 billion. Therefore, although methodologies to estimate the wider macro-economic losses from port disruptions do exist, the existing studies focus primarily on specific port case studies and hypothetical disruption scenarios. They do not, however, include the way such port disruptions materialize, both due to direct asset exposure or due to indirect network effects (inside or outside the port boundaries), and the likelihood of such disruption pathways occurring. The potential magnitude of such ripple effects to the wider economy depends on network configuration and the interconnectivity of the network that is disrupted. For instance, the economic implications of local critical infrastructure disruptions might stay confined to the local economy (e.g., firms that store goods in ports), whereas disruptions to global maritime networks can affect multiple ports and supply-chains at the same time. Hence, the potential for economic spillovers increases in size when going from local to global (see Figure 1).

Figure 1

Critical infrastructure network failure propagation

The interdependency of critical infrastructure network components within port boundaries may affect port operations directly and indirectly. In Figure 2, we can observe that initial damage to a critical infrastructure asset (in layer c) causes a first-order disruption at the port, wherein the direct interdependency of this asset with the port is affected. Since the affected port is connected to other assets and layers, we trace the second-order disruption effects, wherein the (inter)dependency links from the port to other assets and networks are also disrupted. As an example of such effects, Winter storm Uri (2021) led to electricity failures across the state of Texas, closing terminals and industrial facilities in Texas ports (e.g., Houston and Arthur) for several days (Cassidy, 2021). In 2021, a cyberattack on Transnet's IT networks, a company managing rail, port and pipeline infrastructure in South Africa, led to major operational disruptions at multiple ports in the country (Reva, 2021). After Hurricane Sandy (2007), the US Coast Guard opened most of the waterways within five days after the hurricane hit the port, but container and oil terminals could not fully resume operations due to damages to the power infrastructure (Comes and Van De Walle, 2014; Sturgis, Smythe and Tucci, 2014). Hence, even though port operations are restored after an extreme event, the full functionality of ports might still be limited due to other infrastructure failure within or surrounding the port area.

Traditional risk analysis frameworks encompass overlaying geospatial hazard data (e.g., flood map, earthquake severity map) with the location of assets within the port domain (together estimate the exposure of such assets). This is combined with so-called vulnerability curves that define how damage to exposed assets translate into damages (e.g., flood depth resulting in damage) and the potential restoration costs of these assets (Meyer *et al.*, 2013). The risk, expressed as the annual expected direct damages, is then found by integrating the various hazard data, and their likelihood, with the estimated damages per event considered (e.g., flood events with different frequency of occurrence). The potential of disruptions due to critical infrastructure failures, highlighted in our framework, are often not included in risk analysis to port areas. In most studies, the port-specific- (e.g., cranes, warehouses) and dependent infrastructure assets (electricity) are considered (Pitilakis *et al.*, 2019), but their interdependencies are not incorporated in the risk analysis, thereby underestimating the damages associated with hazard occurrence. One detailed study for the Naval Station Norfolk Virginia (Burks-Copes *et al.*, 2014) created an asset inventory of all critical port-related assets and their interdependencies, and used a Bayesian network approach in combination with a large number of present and future storm surge scenarios to assess the risk to the operations of the military base. Another study (Beyeler *et al.*, 2004) created a infrastructure network model in which port operations were dependent on telecommunications networks. Next, a disruption scenario of the communication system was modelled, and the economic losses evaluated. Such infrastructure interdependency models, or systems-of-systems models (Thacker, Pant and Hall, 2017), are becoming more popular in infrastructure failure and system-wide resilience analysis (Thacker, Pant and Hall, 2017; Pant *et al.*, 2018). For instance, Thacker, Pant and Hall (2017) analysed the consequences of flooding to the United Kingdom electricity network and its consequences for airport operations. A similar framework could be easily applied to the national electricity and port infrastructure systems or extended to multiple critical infrastructure interdependencies related to ports.

Incorporating local critical infrastructure interdependencies can improve the port-level economic disruptions models. Using network modelling approaches, different failure mechanisms can be identified, including their likelihood of occurrence and realistic disruptions scenarios (e.g., how long does it take to restore the network). This is essential, since previous analysis clearly showed that longer disruptions can severely amplify losses (Park *et al.*, 2008; Paul and Maloni, 2010; Koks and Thissen, 2016). In addition, these model frameworks can incorporate elements of infrastructure network resilience. For instance, failure of an electricity substation might not cause a disruption if backup generators are installed. Although small-scale disruptions often only result in losses to the local economy, large-scale disruptions to critical infrastructure assets that affect ports operations can further propagate to the hinterland transport (as freight flows cannot be handled) or even to other ports globally (Figure 2), as illustrated by the 2021 Transnet disruption that affected raw material exports from South Africa, Zambia and the Democratic Republic of the Congo (Reva, 2021).

Figure 2

Port-hinterland network failure propagation

Disruptions to hinterland transport networks due to climate extremes can affect freight flows going through ports without causing any damages to the port infrastructure itself. This is shown in our framework, Figure 3, where the first-order disruption to the direct interdependency *hinterland linkage to the port* (layer b) further triggers second-order disruption effects in the global maritime transport network (layer a). In 2018, the water levels of the Rhine at Kaub reached a critical low level, disrupting millions of tons of goods from and to the Belgium and Dutch seaports (NY Times, 2018). Flooding of the Mississippi river in 2011, resulting in parts of river being closed off to barges, resulted in a reduced throughput of the port of Louisiana (Verschuur, Koks and Hall, 2020). The ability to reroute goods in case hinterland transport networks are disrupted, in particular low-cost bulk products (e.g., grain, coal), is often limited due to the rigidity of the system and the cost-efficiency of one mode versus the other. For instance, given the low cost of inland water transport, compared to road and rail in Europe, substitution to road and rail during extreme droughts is very limited (Jonkeren *et al.*, 2014). Again, such impacts can further ripple globally, as they prevent both the exports and imports of goods to demand and production centres, if no alternative routes or mode is available (Figure 3).

In fact, the vulnerability of hinterland transport networks can often be the main systemic risk driver of ports. For instance, an analysis of the impacts of sea-level rise to the city of Los Angeles highlighted that some of the main highway roads surrounding the port of Los Angeles are vulnerable to coastal flooding (Aerts *et al.*, 2018), while the port terminals are elevated sufficiently high (Sriver *et al.*, 2018). For the port of Manzanilla, heavy precipitation events that flood the access roads and railways were identified as the main bottlenecks that can halt port operations (Canevari *et al.*, 2015). Often, the last mile connectivity to ports depends upon one or two road linkages that are often very congested during normal operations (Department of Transport, 2018), and during disasters cargo trucks can be stranded on these access road for several days (Bonato, 2017).

So far, the exposure of road (Koks *et al.*, 2019; Colon, Hallegatte and Rozenberg, 2020), rail (Koks *et al.*, 2019; Zhu *et al.*, 2020) and inland waterways (Jonkeren, Jourquin and Rietveld, 2011; Pant, Barker and Landers, 2015; Christodoulou, Christidis and Bisselink, 2020) transport systems to climate extremes has been assessed separately. However, it remains unclear how individual ports are affected by such transport failures. Jones et al. (2011) consider a disruption scenario where the rail service of the Los Angeles/Long Beach ports is disrupted (transporting 58% of containers to the hinterland), finding limited potential for substitution of imports/exports to other ports due to capacity constraints and lack of railway access.

Given the scarcity of studies, there is a clear need to expand risk analysis to the wider port region and hinterland, in order to include important hinterland networks and identify and quantify the implications of transport disruptions to the connecting seaports. A possible way to approach this is to set up a multi-model transport model, as has been done on a national (for instance for the United States, Australia, Vietnam) and continental scale (e.g., Europe) (Jones *et al.*, 2011; Park *et al.*, 2011; Martínez, Kauppila and Castaing, 2015; de Jong *et al.*, 2017; Berli, Bunel and Ducruet, 2018; Oh *et al.*, 2019), and model disruptions to hinterland transport networks and the changes in freight flows to ports. Hence, by aggregating all possible hinterland disruption scenarios for each port, and by quantifying the potential freight losses or extra re-routing costs of the events, a port-hinterland risk metric could be constructed which can complement the risk analysis framework of the local critical port assets as described above.

Disruptions to hinterland transport networks initially only affect the regional hinterland and part of the trade flows going through ports. However, disruptions have the potential to propagate to other hinterlands through port-level trade connections (e.g., upward propagation) in case trade cannot be rerouted to other transport networks or other modes. To represent the wider supply-chain losses, the aforementioned transport models should be coupled to an economic model that represents port and hinterland systems and the national supply-chain dependencies on these transport systems. Such models have been set-up on a national scale, in both developed (United States) (Park *et al.*, 2011) and developing nations (e.g. Vietnam) (Oh *et al.*, 2019), but hitherto not used for disruption analysis of port networks. Such models can help to quantify the costs of rerouting and identify when certain trade bottlenecks occur in the port-hinterland network. The same models can be combined with realistic scenarios of climate hazards and their likelihood of occurrence (Oh *et al.*, 2019). Some hinterland transport networks may be frequently disrupted but have relatively small macro-economic losses (e.g., winter storms causing local flooding), whereas other networks have a low probability of being disrupted but with large consequences (e.g., drought affecting major navigable river). Moreover, such an integrated transport and economic framework should include assumptions how the economic and transportation systems are able to cope and respond to these disruptions.

Figure 3

Maritime transport network failure propagation

Disruption to the global maritime transport network (MTN) (either to a port or the trade route) can cause a propagation to topologically connected ports and may cause a re-organisation of the network (Figure 4). For instance, during and after the disruption of the port of Kobe due to the 1995 earthquake, transhipment flows were diverted to Busan and Kaohsiung and never returned to Kobe after reconstruction (Chang, 2000). Maritime transport failures can cause large-scale ripple effects, affecting multiple hinterlands (shown in the second-order impacts in Figure 4), as illustrated by the blockage of the Suez canal (2021) that showcased the potential for large scale disruptions to maritime transport and global supply-chains (Yergin, 2021).

The risk of failures within, and the potential adaptation of, the maritime transport network is closely related to the position and interconnectivity of the port within this network. A large number of studies have focused on analysing maritime transportation networks from a complexity science perspective (Kaluza *et al.*, 2010; Ducruet, 2016, 2017; Lhomme, 2016; Viljoen and Joubert, 2016; Calatayud, Mangan and Palacin, 2017; Peng *et al.*, 2018; Kojaku *et al.*, 2019; Pan *et al.*, 2019; Xu *et al.*, 2020; Kosowska-Stamirowska, 2020), thereby uncovering the topological and hierarchical properties of the network and various network indicators of ports. Viljoen and Joubert (2016), for instance, found that the network is robust against targeted attacks, which captures how the network loses connectivity after removing a port from the network. Ducruet (2016) analysed the vulnerability of the maritime transport network to disruptions of the Suez and Panama Canal, finding that ports in Asia, Europe and North America are critically dependent on the functioning of the canals. However, most of the above-mentioned studies use network metrics to predict theoretical vulnerabilities of the system, where it is assumed that no adaptation in the network will take place (e.g., rerouting). Limited evidence of actual network disruptions has been analysed, including an understanding of the mechanisms which govern network re-organisation during and after disruptions. Kosowska-Stamirowska (2020) did empirically investigate the network re-organisation during the 1995 Earthquake that affected the port of Kobe, finding that ports with a large number of common neighbours with Kobe did increase their trade flow, likely driven by the ease of rerouting.

Studies that test various hypotheses of theoretical network vulnerability supported by empirical evidence are much needed in order to better understand the resilience of the network in reality. From a risk analysis point of view, three steps are needed. First, there is a clear need to add information on the probability of various disruptions, as targeted attacks (or other node removal strategies), often employed in network science studies, lack information on how likely it is a single port, or multiple ports at the same time, are affected by an extreme event. Second, the consequences of port disruptions, such as the amount of trade disrupted or the wider macro-economic losses, should be added to the analysis, allowing one to combine the likelihood of port disruptions with the resulting economic repercussions. Third, one should characterize how the system can cope and adapt to such network perturbations at the port (i.e., emergency recovery, protection recapture) and network-level (i.e., rerouting), to quantify how the negative impacts of network disruptions can be partly or fully buffered. For instance, several studies have constructed detailed liner assignment models that can be used to simulate vessel rerouting as a result of port or route disruptions (Li, Qi and Lee, 2015; Novati *et al.*, 2015; Achurra-Gonzalez *et al.*, 2019). Although these models can evaluate the rerouting and delay costs of vessel reassignment, the complexity of such models makes it hard to scale them up to a larger scale (beyond a small number of ports), which is needed given the global extent of the MTN. Therefore, a reduced complexity global maritime transport model, that allows simulating rerouting options under capacity and other constraints (e.g., technical), is highly desirable for maritime disruption analysis. Such models do exist (Tavasszy *et al.*, 2011; Martínez, Kauppila and Castaing, 2015), but have, to the best of our knowledge, not yet been utilised for systemic risk analysis.

Given the large concentration of trade flows on certain strategic routes (e.g., Suez Canal, Panama Canal) and major ports (Verschuur, Koks and Hall, 2021), the potential for widespread economic spillovers are also prevalent. Similar as with the port and hinterland transport network, to quantify the wider economic losses from maritime transport disruptions, the maritime transport models should be coupled to global supply-chain data in order to understand how ports are embedded in these supply-chains. Such information is essential to allocate international freight flows, and understand the ability, and associated costs (e.g., transport delays), of vessel rerouting in case of maritime transport disruptions. Rose and Wei (2013) show that in case of port disruptions, rerouting of goods to other ports can reduce supply-chain losses considerably. However, the extent to which rerouting to other ports is feasible depends, among others, upon the spare capacity in those ports and their hinterland transport connections, the type of good, and the technical constraints of the substitute ports (Trepte and Rice, 2014). Hence, without incorporating such constraints and rules in transport models, understanding whether goods can be rerouted, if a trade disruption occurs, is hard to quantify. Similar, large-scale macro-economic disaster models can simulate how firms use imports from other countries in case inventories are not able to buffer the supply shortage of goods (Koks and Thissen, 2016). However, whether global transport systems are able to supply these goods from alternative countries has not yet been tested, as it could be that they rely on similar ports or trade routes as the initially disrupted ones.

Figure 4

Improving resilience to systemic risks

The systemic risks to various networks, as conceptualized by our framework, can be reduced by incorporating resilience at the appropriate network layer in both the individual nodes (port-level adaptation), the edges (rerouting), and the network as a whole (network restructuring). Appropriate strategies depend on the size of risk (e.g., small-scale or large-scale) and the network components that are disrupted. A useful way to look at this is from a risk layering perspective (Mechler *et al.*, 2014), in which suitable risk and resilience options can be identified by differentiating between levels of risk (e.g., probability of occurrence) and the systemic risks to the system. Adopting a port risk layering framework can help identify combinations of interventions that effectively buffer against systemic risks.

Traditionally, much of the literature has focused on evaluating the benefits of improvements to port assets (nodes) and critical infrastructure networks. For higher frequency events, this includes, for instance, the construction of seawalls and breakwaters to prevent wave penetration (Sierra, 2019), or improved drainage and pavement of ports to cope with heavy rainfall (Canevari *et al.*, 2015). In addition, ports can partly recapture delayed cargo after small disruptions by temporally increasing their productivity (Verschuur, Koks and Hall, 2020). For lower frequency events (e.g. coastal floods), interventions such as elevating port boundaries or access roads have been considered (Becker, Hippe and Mclean, 2017; ARE, 2018; Hanson and Nicholls, 2020). Taking critical infrastructure dependencies into account also widens the scope of interventions. For instance, back-up generators or spare parts can buffer critical infrastructure disruptions and speed-up recovery in case of any asset damage.

The benefits of improved network resilience within the hinterland and maritime transport network are not well addressed in the literature so far. Within the hinterland transport network, cargo flows can be rerouted to other alternative routes or modes of transport. However, as mentioned before, the ability to reroute goods critically depends on the availability of alternative routes/modes, the rerouting cost and capacity, and the type of good (Jonkeren *et al.*, 2014; Friedt, 2018). For the maritime network, for instance, resilience can be improved by having spare capacity in the port system or being able to divert cargo flows effectively. For instance, Achurra-Gonzalez *et al*. (2019) evaluated how the degree of cargo diversion between the six main ports in the Le Havre-Hamburg range influences the economic costs (i.e., costs of delays) of the modelled port disruption. The authors show that for small-scale disruptions (e.g., disruption level between 20 to 40% of the total amount of goods), the resulting disruption costs differ with an order of magnitude depending on the cargo diversion rate. For instance, in the case of the port of Bremerhaven and Rotterdam, the disruption costs are approximately 64.5 million USD per week in case no cargo can be diverted, being only 1.5 million USD/week in case all cargo could be diverted. Similarly, Akakura et al. (2015) assessed the benefits of temporarily ramping up capacity in unaffected Japanese ports to divert cargo flows during a hypothetical earthquake event. In particular, during large-scale port disruptions, where delays are not acceptable anymore, such resilience options within the hinterland and maritime transport network are essential to buffer economic losses. Hence, adding flexibility to the hinterland network is a strategic option for network resilience. The development of dry ports (Cullinane, Bergqvist and Wilmsmeier, 2012), which aim at improving the accessibility between seaports and inland areas and relieving ports from congested freight flows (Nguyen and Notteboom, 2019), may add increasing flexibility to the system and prevent trade flows from growing in at-risk ports.

For small-scale events, firms can buffer delays or shortages by making use of inventories. For large-scale events, when inventories are exhausted and resilience options in the transport network are not available, time consuming, or costly, firms can adopt other resilience options. For instance, as mentioned before, they can try and source products from alternative suppliers, if such products are sourced in case of port disruptions or, alternatively, and if possible, change the type of product used within the production process (Rose and Wei, 2013). However, this is often costly and time consuming, or in case of very specialised supply-chains, hard to achieve. In addition, firms and carriers can incorporate resilience in their supply-chains by diversifying the suppliers and transport routes used, which may cause risk-sharing across different supply and transport network components. This can prevent losses from large-scale network disruptions, with a trade-off between the costs of setting up such a diversified network and the likelihood of large-scale supply disruptions occurring.

Conclusion and directions for future research

This article presents a systemic risk framework for a multi-scale port network that allows the identification and quantification of systemic risks due to network failures on a local, regional or global scale as a result of natural hazards or other extreme events. Various systemic risk modelling frameworks are discussed, and critical gaps are highlighted in the current state-of-the-art risk modelling. The systemic risk framework allows one to identify how failures to the critical networks -local, hinterland and global maritime networks- propagate from local to regional to global scale. This leads to various options to improve the resilience of the network depending on how this risk materializes to the different networks.

Moving from a traditional risk framework, which solely focuses on the risk to individual assets within the different networks, to a systemic risk framework requires a shift in thinking on how the risks from natural hazards are identified and managed. For instance, ports can adopt very strong adaptation strategies to combat climate-related risks, but freight flows can still be hampered if the ports they trade with are not doing the same thing, or if they rely on hinterland transport networks that are frequently disrupted. Given the expected increase in the frequency and intensity of climate-related risks, thereby increasing the potential for disruptions throughout the different networks, system thinking will be essential to identify bottlenecks and target investments. This therefore requires an integrated approach between the port authorities (that are (often) responsible for the port infrastructure), national governments (that own, maintain and invest in hinterland transport networks), carriers and logistics providers (that determine the transport routes taken) and firms (as they need to incorporate risk information in their supply-chain management strategies). As infrastructure investments can lock-in certain network structures (e.g., transport investments will lead to concentrated flows on certain routes), systemic risks need to be identified and incorporated in planning decisions.

Often, risks to the various network elements, and the way they can propagate across networks, are not known, or not available in a way that allows decisions to be made to improve resilience. Most importantly, risk information needs to be supported by data, which is often hard to obtain on a large-scale or in a detailed enough format to allow performing detailed risk analysis. Based on the summary of studies that have been carried out, and recent advances in performing large-scale asset level risk analysis, we could identify potential ways forward in quantifying systemic risks.

For the local critical infrastructure risk analysis, ports authorities can expand the detailed climate risk and adaptation analysis by better understanding the interaction between the infrastructure assets and considering how failure of one of the assets can affect the whole network. Approaches to do this can range from relatively simple failure tree methods (Abdelhafez, Ellingwood and Mahmoud, 2021), in which potential failure pathways and dependencies are identified, to more complex approaches such as Bayesian network modelling (Burks-Copes *et al.*, 2014) or system-of-system approaches (Thacker, Pant and Hall, 2017).

To perform regional or national hinterland risk analysis, two pieces of information are essential. First, information on the use of different hinterland infrastructure networks (e.g., the modal split), either close to the port or further in the hinterland. Second, one needs to understand the resilience that is already embedded in the system. For hinterland transport networks, this mainly concerns the ability to reroute goods, either to other routes or other modes in case of a disruption (Oh *et al.*, 2019). Often, this data does not exist and needs to be derived from freight models. Although freight modelling is generally data intensive, examples exist of the development of freight models in more data-scarce environments (Simpson *et al.*, 2021), which can form the basis for setting up such a model in different contexts.

Systemic risk analysis of global maritime networks requires similar information as the hinterland transport risk analysis. Although it is known how trade flows from one country to another, and how ports are connected to maritime transport routes, information on how trade flows through ports connect and integrate global supply-chains with each other is not readily available (Verschuur, Koks and Hall, 2021). Similarly, information about the resilience that is already embedded in the maritime transport system, and how this differs per port, country or economic sector, is needed to perform large-scale systemic risk analysis. Nonetheless, as global risk analysis to ports is now becoming feasible (Izaguirre *et al.*, 2021), and global supply-chain data is available (Lenzen *et al.*, 2017), integrating this information in a risk framework would be possible in the near future. In addition, innovative data sources, such as the Automatic Identification System (AIS), can support this development by providing detailed information on port-level trade activity on a global scale in almost real-time (Verschuur, Koks and Hall, 2021).

As global supply chains are becoming increasingly integrated and the threats to the port network from climate change induced natural hazards and man-made disruptions are becoming more frequent, efforts to enhance system-wide resilience should be considered, alongside port adaptation, to prevent supply-chain losses to exacerbate in the future. Therefore, moving from a traditional risk framework towards a systemic risk framework to quantify port and supply-chain risk should be a combined effort of the different actors involved, and a closer integration between risk modellers and maritime experts.

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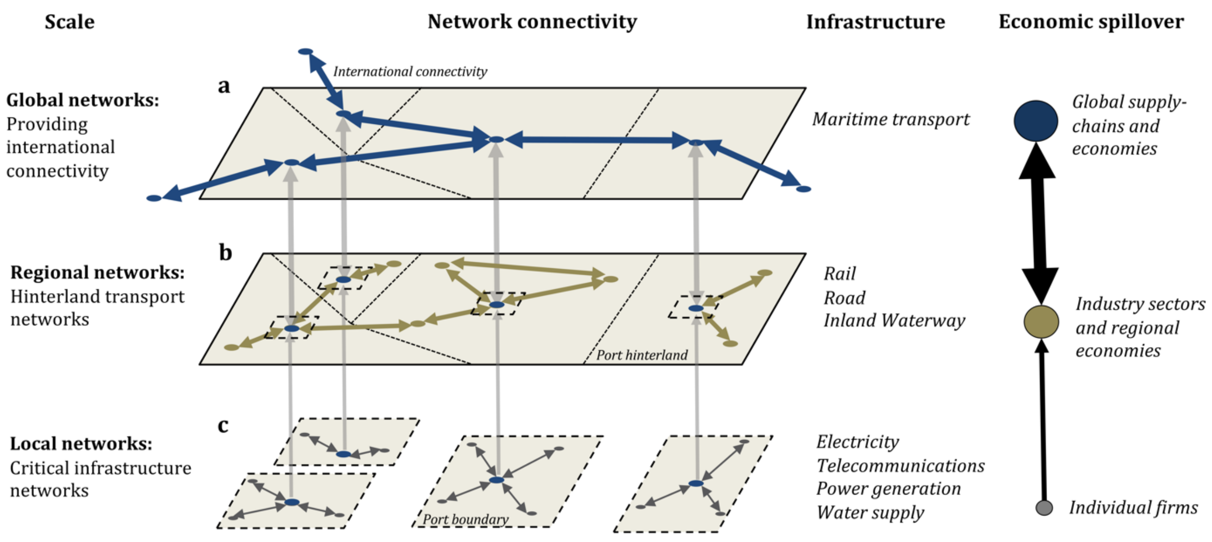

Figure 1: The multi-scale port framework depicting the local, regional and global networks that ports are embedded in.

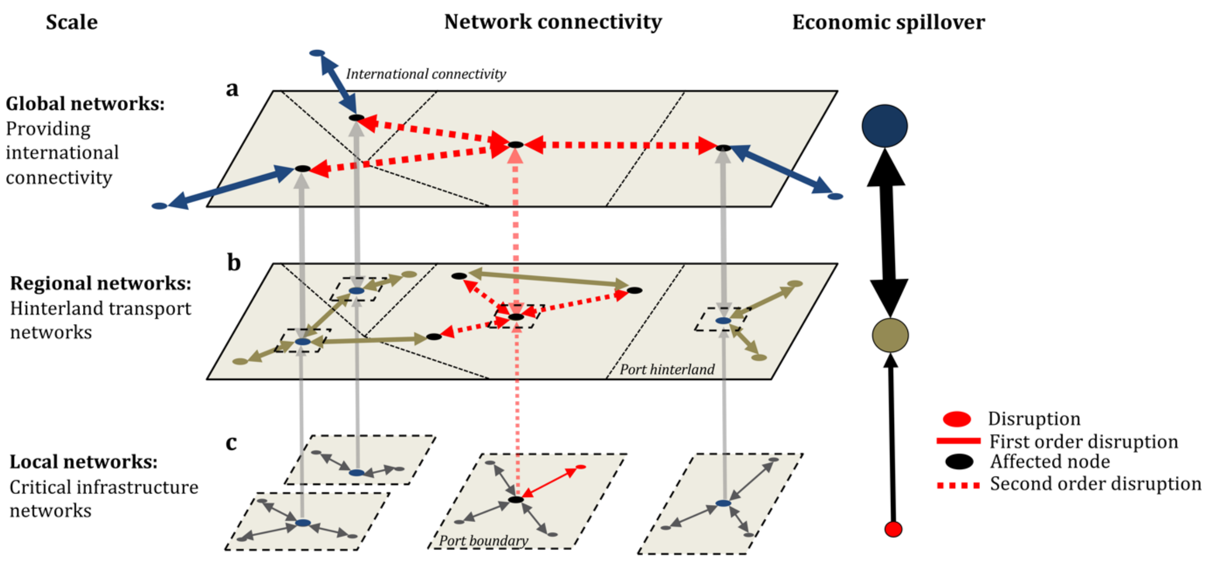

Figure 2: The multi-scale port framework showing how a local infrastructure failure, disrupting a port, can further propagate up to the connected networks.

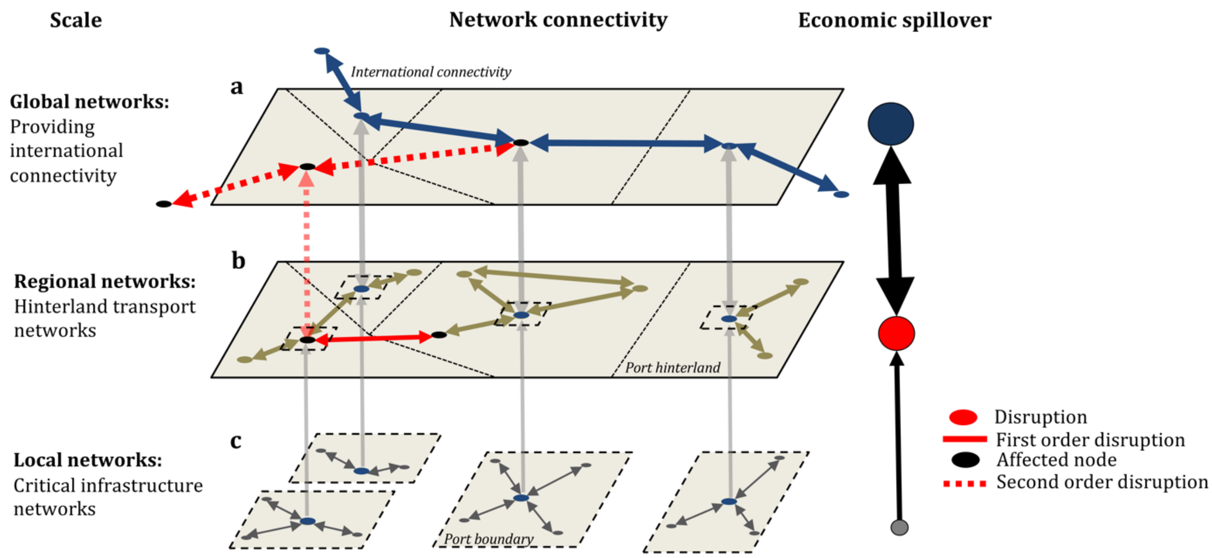

Figure 3: The multi-scale port framework showing how a hinterland transport disruption can further propagate horizontally to connected ports, and vertically to other ports.

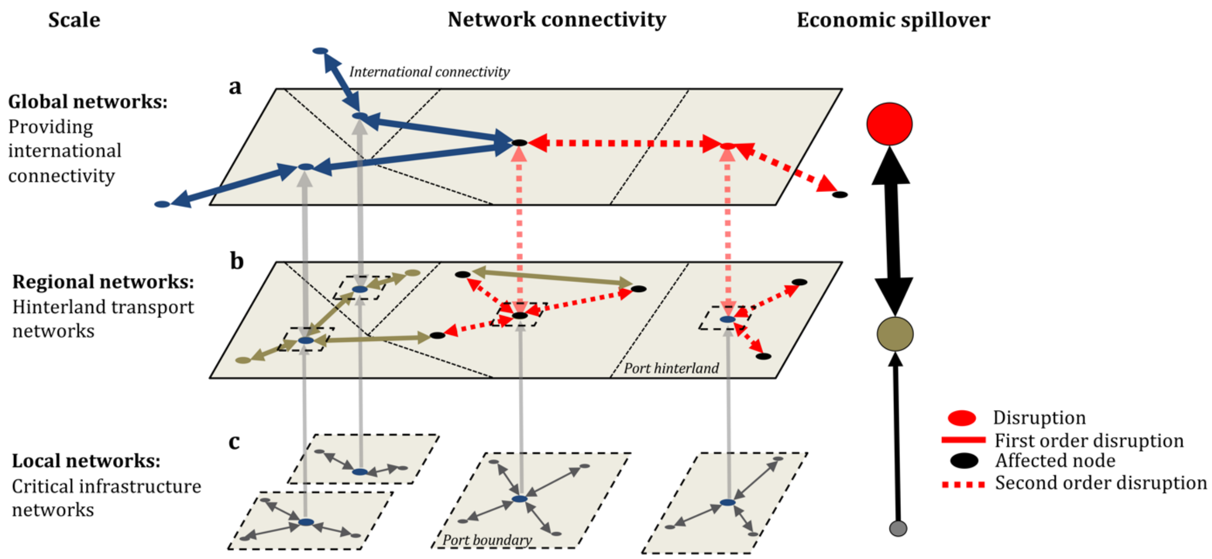

Figure 4: The multi-scale port framework showing how a port disruption can further propagate horizontally to connected ports and hinterland areas.