Present and future climate risks to global port infrastructure and maritime trade flows

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“Maritime transport is the backbone of global trade and the global economy ... yet the vast majority of people are unaware of the key role played by the shipping industry, which is largely hidden from view.” — ***Ban Ki-moon, Former UN Secretary-General***

“Although nature commences with reason and ends in experience it is necessary for us to do the opposite, that is to commence as I said before with experience and from this to proceed to investigate the reason.” — ***Leonardo da Vinci***

“We live in a world full of contradiction and paradox, a fact of which perhaps the most fundamental illustration is this: that the existence of a problem of knowledge depends on the future being different from the past, while the possibility of the solution of the problem depends on the future being like the past.” — ***Frank Knight***

ABSTRACT

Ports are vulnerable to the impacts of climatic extremes and natural disasters, which are expected to become more severe as a result of climate change. The occurrence of hazardous events can damage physical assets (i.e. physical asset risk) and disrupt port operations, resulting in downtime (i.e. downtime risk). The inoperability of ports, delaying or disrupting trade flows, could further result in wider economic losses that could spill over across borders through maritime transport and supply-chain networks (i.e. systemic risk).

This thesis aims to quantify present-day and future climate risks to port infrastructure and maritime trade flows using a novel maritime-economic systems framework and a detailed port-level risk analysis. In doing so, it provides insights into (1) the dependencies between global supply-chains and the maritime transport network, (2) the physical asset and downtime risks that ports face globally from multiple hazards and the trade flows exposed to this (combined called climate risk), and (3) the change in climate risk in the future as a result of climate change and growth in trade, requiring new port expansions.

The maritime-economic systems framework presented in this thesis underlines that ports, maritime transport and global supply-chains are tightly coupled with feedbacks and critical dependencies. In particular, the findings show how every dollar of port throughput is associated with 4.3 dollar of economic activity, and that some 40 ports facilitate trade that is critical for >10% of the domestic economic activity of countries they serve. The results further show that low income countries and small island developing nations are

disproportionately reliant on their ports for the well-functioning of their economies, despite the small amount of freight going through these ports, emphasising that an integrated framework, as presented in this thesis, is needed to identify critical links between ports and the economy.

This thesis further finds that the vast majority of ports (86%) are exposed to more than three hazards out of the six considered. The climate risks to ports a result of physical asset damages and revenue losses reach 6.5 USD billion per year globally at present, but is expected to increase by a factor 2.5 – 6.0 by 2050 due to climate change (increasing the risk by a factor 1.7 – 2.2) and the trade growth, requiring 1353 – 5735 km^2 of new port expansions. On top of these climate risks, 63 USD billion of port throughput is at risk every year due to port downtime, which could be up to 230 – 500 USD billion by 2050. These findings highlight that (1) adaptation is urgent, irrespective of climate and trade scenarios, (2) new port expansions face large planning uncertainties, which should be accounted for in planning and design, and (3) the value of the trade at-risk is large compared to the climate risk quantified, indicating that systemic risks can be significant if trade disruptions occur and ripple through supply-chains. However, all risk results are sensitive to parameters that determine a port's resilience, highlighting that local resilience information is needed to refine the risk results, and that the critical resilience parameters vary considerably across ports, requiring tailored solutions to improve resilience.

Altogether, this thesis provides a blueprint for a shift in risk thinking, moving from a port-centric risk perspective towards a system-wide risk perspective of the coupled maritime and economic system. The information provided in this thesis is critical to inform maritime actors of the present and future climate risks they face, which can further guide adaptation decisions, support (long-term) infrastructure planning and design, and build resilience in the global supply-chain network. Ultimately, this will help safeguard the sustainability of port operations, maritime transport and economic development in the near and distant future.

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PUBLICATIONS

The work presented in Chapter 3 to 7 has appeared or has been submitted to the following peer-reviewed journals:

1. **Verschuur**, Koks and Hall (2020), Port disruptions due to natural disasters: Insights into port and logistics resilience, *Transportation Research Part D: Transport and Environment*, 85 (102393) (**Chapter 3)**

2. **Verschuur,** Pant, Koks and Hall (2022), A systemic risk framework to improve the resilience of port and supply-chain networks to natural hazards, *Maritime Economics and Logistics* (**Chapter 4)**

3. **Verschuur,** Koks and Hall (2022), Port's criticality in international trade and global supply-chains, *Nature Communications*, 13 (4351) (**Chapter 5)**

4. **Verschuur**, Koks, Li and Hall, Multi-hazard risk to global port infrastructure and resulting trade and logistics losses, *under review in Communications Earth and Environment* (**Chapter 6)**

5. **Verschuur,** Li, Martinez, Koks, and Hall, Climate risks to port infrastructure expansions for future global trade, *to be submitted* (**Chapter 7)**

Other peer-reviewed publications based on the work presented in this thesis are:

- **Verschuur**, Koks and Hall (2021), Observed impacts of the COVID-19 pandemic on global trade, *Nature Human Behaviour*, 5 (3)

- **Verschuur,** Koks and Hall (2021), Global economic impacts of COVID-19 lockdown measures stand out in high-frequency shipping data, *PLOS ONE,* 16 (4)

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1 INTRODUCTION

1.1 Background

Ports are critical nodes in the global economy, connecting supply-chains and consumer markets across borders (Ng *et al.*, 2015; Becker *et al.*, 2018). 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; Izaguirre *et al.*, 2021). The impacts from natural hazards can materialise as direct damages to physical assets and revenue losses to terminal operators due to port downtime. For instance, Hurricane Katrina (2005) caused an estimated 1.7 USD billion in direct damages to South Louisiana ports (Santella, Steinberg and Sengul, 2010), while the 1995 Great Hanshin earthquake damaged facilities at the port of Kobe worth 10 USD billion (Chang, 2000). Cyclone Yasi (2011) closed the port of Brisbane for ten days, resulting in large revenue losses to terminal operators by decreasing the annual throughput by six percent (Cahoon *et al.*, 2016).

The direct damages to infrastructure assets and revenue losses due to downtime do not cover the full range of economic losses associated with hazard impacts to ports. Because of the integration of the maritime transport network within, and the mutual dependencies on, global supply-chains, local port disruptions can potentially trigger spill-over effects to global maritime transport and supply-chains networks (Rose and Wei, 2013; Levermann, 2014; Becker *et al.*, 2018). Such spill-over effects, also called systemic risks, could initiate and amplify macroeconomic losses, which could exceed the physical asset damages (Koks and Thissen, 2016; Wei *et al.*, 2022). For instance, damages from Hurricane Katrina in 2005 led to almost 900 USD million in agricultural trade losses due to transport disruptions alone (Trepte and Rice, 2014). Damages to port facilities as a result of the Great East Japan Earthquake (2011), restoration of which took up to a year, led to a severe disruption of container flows, causing a shock to the supply-chains of many companies, in particular vehicle manufacturers (Akakura *et al.*, 2015).

The risks associated with physical asset damages, operational downtime and systemic impacts are expected to rise in the future as a result of climate change and the continuous growth of freight handled by ports. Climate change may increase the frequency and severity of climate-related extreme events, causing more frequent operational disruptions (Izaguirre *et al.*, 2021) or permanent inundation of exposed port terminals (Christodoulou, Christidis and Demirel, 2019; Allen, McLeod and Hutt, 2021). On top of that, global freight flows are expected to triple in size by 2050 compared to 2015 (ITF, 2015), requiring additional port capacity and infrastructure to meet this demand (Hanson and Nicholls, 2020), increasing the amount of infrastructure located in at risk areas. Despite the huge challenge of adapting existing and new port infrastructure to cope with a changing climate, it has been argued that, at present, port authorities have low awareness of the potential threats of climate change, lack clarity on how and when to respond to climate change, and, as a consequence, only limitedly consider adaptation measures in long-term planning and design (Becker *et al.*, 2012; UNCTAD, 2017a; Sweeney and Becker, 2020).

Given the magnitude of potential economic losses associated with port disruptions now and in the future, there is a clear need for an integrated risk framework that enables quantifying the various climate risks that ports face and how they could spill over to other ports and the wider economy. Considering the global nature of the coupled transport and economic system, this integrated risk framework should be locally refined to adequately capture risks to individual infrastructure assets, though global in extent to fully capture potential systemic risks.

Quantifying present and future climate risks is not only important for understanding the magnitude and spatial distribution of risk to ports and economies, but also allows for the quantification of adaptation needs (e.g. to keep risk tolerable) and, subsequently, the evaluation of strategies to improve resilience within the coupled maritime and economic system. Improving resilience can be done through strengthening and adapting port terminals (e.g. elevating terminals, improved drainage) (Esteban, Takagi and Shibayama, 2016; Gracia *et al.*, 2019; Sierra, 2019), adding flexibility to the maritime transport network (e.g. rerouting of goods) (Novati *et al.*, 2015), or buffering supply and demand shocks within the supply-chain networks (e.g. inventories, input substitution) (Rose and Wei, 2013; Wei, Chen and Rose, 2020). Altogether, such an integrated systemic risk framework provides critical information for a variety of stakeholders involved in the maritime supply-chain, and helps to prioritize adaptation decisions, inform long-term infrastructure planning and build resilience in the global supply-chain network.

1.2 Research gaps

Despite progress in quantifying climate risks to ports, maritime and supply-chains, several research gaps remain.

1.2.1 Lack of empirical evidence of port disruptions from natural hazards

Several surveys of port authorities have inferred what ports' operators perceive as the most disruptive climate-related hazard and what critical thresholds could suspend operations or damage infrastructure (Becker *et al.*, 2012; UNCTAD, 2017a). Such surveys provide contextual information on the experiences of port authorities with respect to past climate extremes, but lack a quantification of the experienced duration of disruptions. Additionally, while a handful of port disruption databases have been constructed (Trepte and Rice, 2014; Lam and Su, 2015; Adam *et al.*, 2016; Cao and Lam, 2019), they often cover only a specific country, are small in sample size, include climate and non-climate related hazards as disruption triggering events, and lack insights into the operational dynamics of these port disruptions. More recently, a small number of studies have explored the use of empirical vessel movement data to analyse the dynamics of specific ports during and after specific hazard events (e.g. Hurricane Sandy, Matthew and Katrina), predominantly in the United States (Farhadi *et al.*, 2016; Touzinsky *et al.*, 2018; Rousset and Ducruet, 2020). However, this approach has not been scaled-up to multiple ports across geographies, which would allow drawing some more generalised conclusions on the duration of disruptions, and the resilience of ports and the maritime network during and after extreme events.

1.2.2 No unified framework of multi-hazard risk to port infrastructure and operations

Detailed hazard risk analysis of the operational vulnerability or the impacts to infrastructure assets of individual ports are prevalent. These risk analyses often combine an asset representation of port infrastructure (e.g. terminals, breakwaters) with a detailed hazard model (e.g. hydrodynamic model) and the value of port infrastructure at risk or the flow of goods through a port (Esteban, Webersik and Shibayama, 2010; Zhang and Lam, 2015; Esteban, Takagi and Shibayama, 2016; Sierra *et al.*, 2017; Bove *et al.*, 2020; Abdelhafez, Ellingwood and Mahmoud, 2021). However, efforts to scale-up these types of analyses to a regional or global scale are limited, and those that do attempt this have major limitations. For instance, large-scale analyses have consistently represented ports as single point locations (Christodoulou, Christidis and Demirel, 2019; Izaguirre *et al.*, 2021; Rozenberg *et al.*, 2021), which fail to capture the exposure of specific infrastructure assets (e.g. cranes, terminals) and how these infrastructure assets are susceptible to hazardous events. On top of that, often only the exposure of ports to a specific event (e.g. a 1-in-100 year event) is considered (Christodoulou, Christidis and Demirel, 2019), and not the full range of probable events, which is needed to quantify risk. Similarly, either a single hazard is analysed, in particular coastal flooding or extreme wind (Simpson *et al.*, 2010; Lam, Liu and Gou, 2017; Christodoulou, Christidis and Demirel, 2019), or a range of operational thresholds (Izaguirre *et al.*, 2021). This makes it difficult to identify the dominant hazard driver across multiple (diverse) hazards on a global scale, in particular comparing and contrasting low-probability but high-impact events (e.g. natural disasters) with high-probability but low-impact events (e.g. operation disruptions). As a consequence, no study has monetised the impacts of natural disasters and extreme weather events to both physical assets (causing physical damages) and operational thresholds that can cause downtime (and consequently trade and revenue losses).

A unified multi-hazard risk framework would therefore allow comparing and contrasting the risk results across ports and hazards. However, three main data and methodological gaps exist to construct such as a unified risk framework. First, the lack of research quantifying physical asset damages on a large scale can be attributed to the fact that, in contrast to other critical infrastructure types (e.g. roads, railways, airports), no global infrastructure database of port terminals exist. Second, given the detailed data required to do risk analysis on a global scale but locally refined level, there are existing computational and data limitations that makes it hard to derive fit-for-purpose hazard data for ports on a global scale. Third, the difficulty of monetising the consequences of operational downtime on a large-scale is related to the limited availability of data on the flow of goods (in weight and value terms) through ports globally.

1.2.3 Limited quantification and generalisation of systemic risks

A disruption of a single port can spill over to other connected ports in the maritime transport network, to countries that depend on this port for import, export or transhipment, or to firms (and hence economic activity) within global supply-chains that depend on trade flows through this port. Systemic risks originate from these interdependencies, and could result in economic losses to any actor that indirectly relies on the port's trade facilitation function. Yet, so far, systemic risks are hardly considered nor quantified. On the one hand, a plethora of network analyses of global maritime transport have emerged over the years, identifying critical elements in the network using targeted or random attack methods (Ducruet, 2016; Viljoen and Joubert, 2016; Calatayud, Mangan and Palacin, 2017; Peng *et al.*, 2018). However, within these studies, actual flows on the network are often not considered, nor the likelihood of failures occurring and the potential response of the system to network failures. On the other hand, detailed freight models or liner assignment models have been developed to study the optimal allocation of flows on the transport network (often for a country or small-scale regional system), including the optimal re-allocation in cases of a disruption (Jones *et al.*, 2011; Novati *et al.*, 2015; Achurra-Gonzalez, Novati, *et al.*, 2019). These studies help to quantify the additional costs of rerouting and the flows that could not be reallocated (i.e. disrupted trade), but only consider specific disruption scenarios, and are too computationally and data intensive to scale up to a larger scale (continental or global). Finally, a number of studies, almost entirely focused on the United States, have coupled the trade flows going through a specific port to a macroeconomic impact model (using input-output tables) to quantify the wider economic losses of port disruptions to the national economy, and the benefits of improved resilience (Rose and Wei, 2013; Wei *et al.*, 2017; Wei, Chen and Rose, 2020). However, scaling such methodologies beyond single port case studies, while also including international supply-chain spill-overs, is constrained by the lack of information on the amount of trade that flows through ports globally, which ports and countries this trade comes from and goes to, and how this trade is used in supply-chains across borders. Only Kuhla *et al.* have very recently attempted to evaluate the global macroeconomic impacts (through supply-chains) of historical typhoons disrupting shipping routes in East Asia (Kuhla *et al.*, 2022). While an ambitious endeavour, in particular their representation of firm behaviour to cope with transport delays, the maritime transport network representation is relative simplified and lacks real-world information on maritime connectivity, flow constraints (e.g. capacity) and port specialisation (e.g. which goods can be handled by different ports). Moreover, this study overpredicts maritime trade flows by excluding the share of aviation in global trade (which transports 30 - 35% of global trade by value).

Altogether, to enable an analysis of global systemic risks, a systems framework of the integrated maritime transport and economy supply-chain networks is needed. This requires a reduced complexity maritime transport model, constrained by bilateral (maritime) trade flows between countries, which can simulate the trade flow allocation on the hinterland transport network, across maritime routes and through ports. By linking such model to global input-output tables, representing cross-border sectoral use of trade flows in production and consumption, it could capture potential international spill-overs of port disruptions to supply-chains.

1.2.4 No quantification of global adaptation needs

The existing literature on port-level adaptation has focused on quantifying the future risks to port operations or assets as a result of climate change, the adaptation options to reduce this, and how much this would cost (Esteban, Takagi and Shibayama, 2016; ARE, 2018; Sierra, 2019; Jebbad *et al.*, 2022). This is often done for a subset of ports on a regional scale. The adaptation options considered are mainly restricted to retrofitting of breakwaters to deal with changing wave conditions and storm surges, and constructing seawalls or elevating port terminals to cope with sea-level rise. Some detailed studies of individual ports also considered other adaptation options, such as drainage upgrades, improved tie-down systems of cranes, and elevating access roads (Stenek *et al.*, 2011; Canevari *et al.*, 2015).

A quantification of the global adaptation needs (e.g. to maintain present-day risk), considering changes in future risk for individual ports globally, has not yet been considered. This would require information on the changing climate risks from different hazards that can be matched with suitable adaptation strategies. Similarly, several studies have emphasised that implementing adaptation upfront into the design of new infrastructure (e.g. port expansions) is much cheaper than having to retrofit this same infrastructure during its service lifetime (if technically or financially feasible) (Sweeney and Becker, 2020). However, the potential to mainstream adaptation in new port expansions hinges on the amount of new port infrastructure needed, where this is needed, and what the present and future climate risks to these locations are. To date, only one study has quantified port expansion needs on a country-level (Hanson and Nicholls, 2020), but not where the likely locations are of these expansions and the climate risks to these new port expansions, limiting such analysis. As such, the evolution of climate risks due to both climate change and port expansions on an individual port-level is lacking in the literature, which would be required for detailed adaptation analyses of existing and new port infrastructure.

1.3 Key terms and concepts

Ports: The definition of a port is ambiguous. In this thesis, a port, or rather a port area, is defined as the physical infrastructure that supports port operations or has direct feedbacks with a port's operational status. This includes the seaside infrastructure (e.g. breakwaters and approach channel), the quayside infrastructure (e.g. jetties, cranes, quays, and yard equipment), and the landside infrastructure (e.g. warehouses, road, rail, pipelines, water, electricity, and supporting industries). Figure 1 provides a visual representation of the port area as defined in this thesis.

Coupled maritime-economic system: While there is no formal definition of the coupled maritime-economic system, in this thesis it is framed as the maritime transport network and logistics services embedded within global supply-chains to connect firms and customers across borders (as schematised in Figure 2). A supply-chain can be broadly defined as the activities and facilities involved in producing a good, and moving it from its origin (e.g. a supplier) to its destination (e.g. a customer), either to consume directly or use as intermediate input. In contrast to some definitions of a supply-chain that describe the concept as the network of firms and markets that interact with each other, the mode of transport and transport route chosen to connect suppliers to customers is critical in the definition adopted here. The transport network, in particular the maritime transport network, is defined as the nodes (e.g. ports and their facilities), edges (e.g. shipping and hinterland transport routes), and the transport capacity and logistics services on these nodes and edges to create physical connections between places.

Climate risk: Risk is commonly defined as the interaction of hazard, (i.e. the likelihood of a particular hazard occurring), exposure (i.e. the people, infrastructure, housing and other tangible human assets located in hazard-prone areas), and vulnerability (i.e. the conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, asset or system to the impacts of hazards) (UNDRR, 2022). Climate risk in this thesis is conceptualised as the risk to ports' physical assets and operations as a result of climate-related hazards. Climate risk is monetised in terms of the physical asset damages and the amount of maritime trade at risk as a result of port downtime, which can further cause losses to logistics actors (e.g. terminal operators, carriers and shippers). In this thesis, the term climate risk, disaster risk and port-specific risk are often used interchangeably, mainly associated with the fact that earthquakes are included in the analysis. While strictly speaking earthquakes are not considered a climate-related hazard, but a geophysical one, it is still included in the climate risk metric as earthquakes cannot be neglected as a potential threat to ports. However, in terms of future climate risk, it is the only hazard that is unaffected by climate change and hence kept constant in the future climate risk analysis. In addition, tsunamis are not considered in this thesis given the lack of reliable global hazard models on tsunami occurrence and their hazard footprint.

Systemic risk: Systemic risk is defined as "*the potential knock-on effects to initially unaffected components of a system because of system interactions or dependencies*" (UNDRR, 2022). Within the scope of this thesis, systemic risks refer to any type of economic loss experienced by actors within the coupled maritime transport and economic system (e.g. trade dependent ports, carriers, shippers, firms) that occur because of hazard impact to a single port. In this thesis, the potential losses to terminal operators, shippers, carriers and the economy (to some extent) are quantified, which capture the systemic risk components. These losses thus cover both private losses to maritime actors (e.g. terminal operators, carriers, shippers), public losses (in case ports are publicly owned), and wider macroeconomic losses (which include both firm output and household and government consumption and can thus be considered a mix of private and public losses). Systemic risks to other actors, such as trade-dependent ports, are not considered but could be easily quantified given the datasets derived.

Resilience: The resilience of a system captures "*its ability to resist, recover from, and adapt to, adverse events*" (Linkov *et al.*, 2014). Given the coupled maritime and economic system under consideration, resilience is embedded within the different interconnected layers. On the port-level (i.e. port resilience), it can be described as the ability of a port to minimise operational downtime or physical damages given an adverse stressor, in this case a climate extreme or natural disaster. On a system-level (i.e. systemic resilience), it refers to the ability of the system to minimise the loss to all actors dependent on the port that is faced with inoperability because of a climate extreme or natural disaster. Hence, the resilience of the system overall depends on the resilience of its individual interconnected components, which depend among others on the port engineering measures (e.g. breakwater design, flood protection), port operational measures (e.g. production recapture, stockpiling, emergency planning), maritime and hinterland logistic measures (e.g. stockpiling, rerouting, mode substitution), and firm-level measures (e.g. inventories, input substitution, import substitution) embedded within the system.

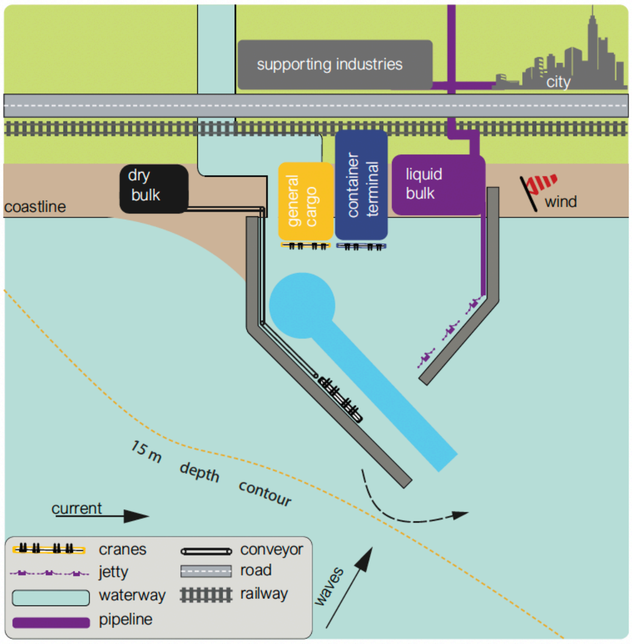

Figure 1.1: Graphic depiction of the definition of port area adopted in this thesis, which includes seaside, quayside, and landside infrastructure, and supporting industries. Source: (Van Koningsveld *et al.*, 2021).

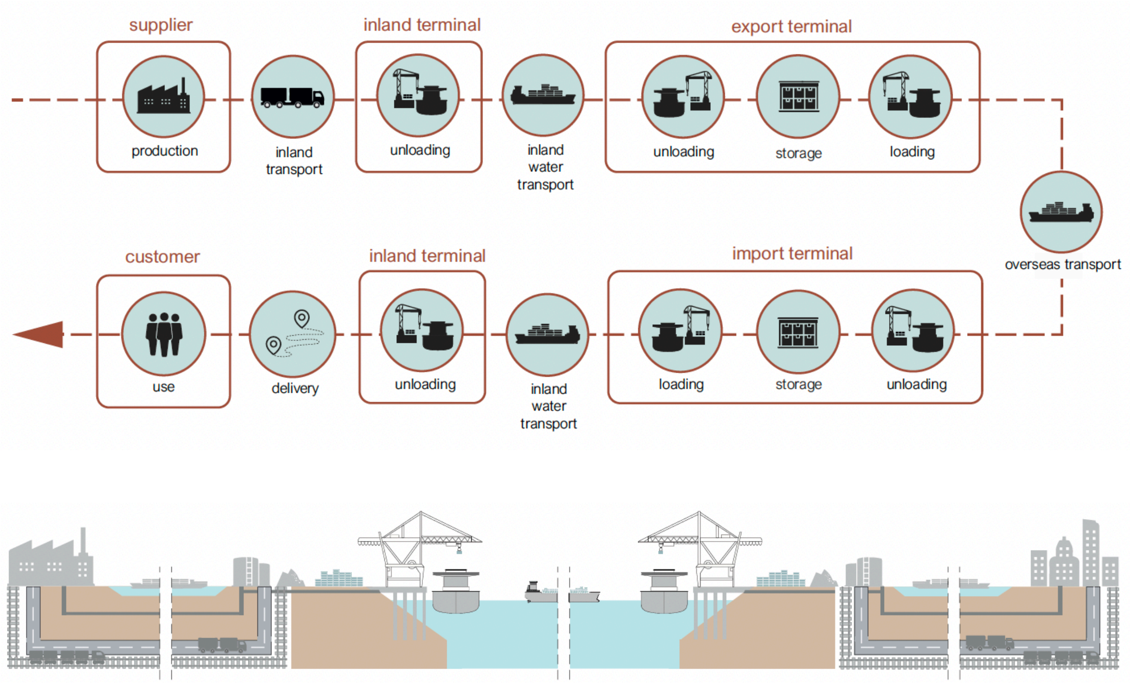

Figure 1.2: A schematic representation of the coupled maritime-economic network in which maritime transport is embedded within the global supply-chain network, connecting firms and consumers across borders. Source: (Van Koningsveld *et al.*, 2021).

1.4 Aim and research questions

The aim of this thesis is to quantify present-day and future climate risks to port infrastructure and dependent trade flows using an integrated maritime-economic systems framework.

To achieve this aim, the following research questions are defined:

1. What is the empirical evidence of past port disruptions due to natural disasters and the resilience of the maritime transport network?
2. What are the necessary elements of a global systems framework of the coupled maritime and economic networks, and how are they interconnected?
3. What is the criticality of ports in international trade and global supply-chains?
4. What are the present-day climate risks to global port infrastructure and the resulting logistics and trade losses?
5. What are the future climate risks to port infrastructure and trade as a result of climate change and the need for new port expansions, and how does this affect the design and planning of new port expansions?

1.5 Thesis structure

This thesis presents five papers to address the research questions set out. Every main chapter is structured around one paper, alongside a literature review (Chapter 2) and synthesis chapter (Chapter 8). Appendix A describes for each paper the authors' contributions following the CRediT (Contributor Roles Taxonomy) taxonomy. An overview of all thesis components and chapter interactions, as well as the overall thesis output, is shown in Figure 1.3.

Chapter 2: Literature review

Chapter 2 provides a review of the existing conceptual, empirical and methodological research that underpins the research presented in this thesis. It includes a general overview of the climate risks to ports, and literature covering (i) empirical evidence of past port disruptions, (ii) risk analyses to ports, maritime transport and the economy, and (iii) climate adaptation in practise.

Chapter 3: Port disruptions due to natural disasters: Insights into port and logistics resilience

Paper: Verschuur, Koks and Hall (2020), Port disruptions due to natural disasters: Insights into port and logistics resilience, *Transportation Research Part D: Transport and Environment*, 85 (102393)

Chapter 3 presents empirical evidence of natural disasters affecting port operations. This information is used to provide insights in the average duration of hazard-induced port disruptions, as well as anecdotal evidence of the resilience of ports and the maritime system to cope with, and recovery from, such disruptions.

Chapter 4: A systemic risk framework to improve the resilience of port and supply-chain networks to natural hazards

Paper: Verschuur, Pant, Koks and Hall (2022), A systemic risk framework to improve the resilience of port and supply-chain networks to natural hazards, *Maritime Economics and Logistics*

Chapter 4 presents a new global systems framework of the coupled port, maritime and economic networks, which can be used to analyse systemic risks to these interconnected system components. This framework will form the basis for the following chapters.

Chapter 5: Port's criticality in international trade and global supply-chains

Paper: Verschuur, Koks and Hall (2022), Port's criticality in international trade and global supply-chains, *Nature Communications*, 13 (4351)

Chapter 5 proposes an integrated framework to couple the global maritime transport network to the wider economy through supply-chain interdependencies. It presents several new metrics of the criticality of ports in international trade and for global supply-chains. This is based on a new global maritime transport model developed, which is linked to multi-regional input-output tables to understand the dependencies between ports and the domestic and foreign supply-chains they serve.

Chapter 6: Multi-hazard risk to global port infrastructure and resulting trade and logistics losses

Paper: Verschuur, Koks, Li and Hall, Multi-hazard risk to global port infrastructure and resulting trade and logistics losses, *under review in Communications Earth and Environment.*

Chapter 6 introduces a multi-hazard risk analysis framework that quantifies the present-day physical asset damages to port and critical (i.e. road, rail, electricity) infrastructure, and the trade and logistics losses as a result of port downtime.

Chapter 7: Climate risks to port infrastructure expansions for future global trade

Paper: Verschuur, Li, Martinez, Koks, and Hall (2022), Climate risks to port infrastructure expansions for future global trade, *to be submitted*.

Chapter 7 explores the need for new port expansions in the future under different trade scenarios that differ based on the degree of socio-economic development, decarbonisation and trade liberalisation. By projecting climate risk into the future given climate change and port expansions, the future risks to port infrastructure and trade are quantified, as well as the planning uncertainties posed to new port expansions.

Chapter 8: Synthesis

Chapter 8 provides a synthesis of the thesis, which include a summary of the key findings, some overarching points of discussion, future research directions and a final outlook.

Appendices

The appendices include the author contributions and statements, followed by the Supplementary Information associated with Chapters 5, 6 and 7.

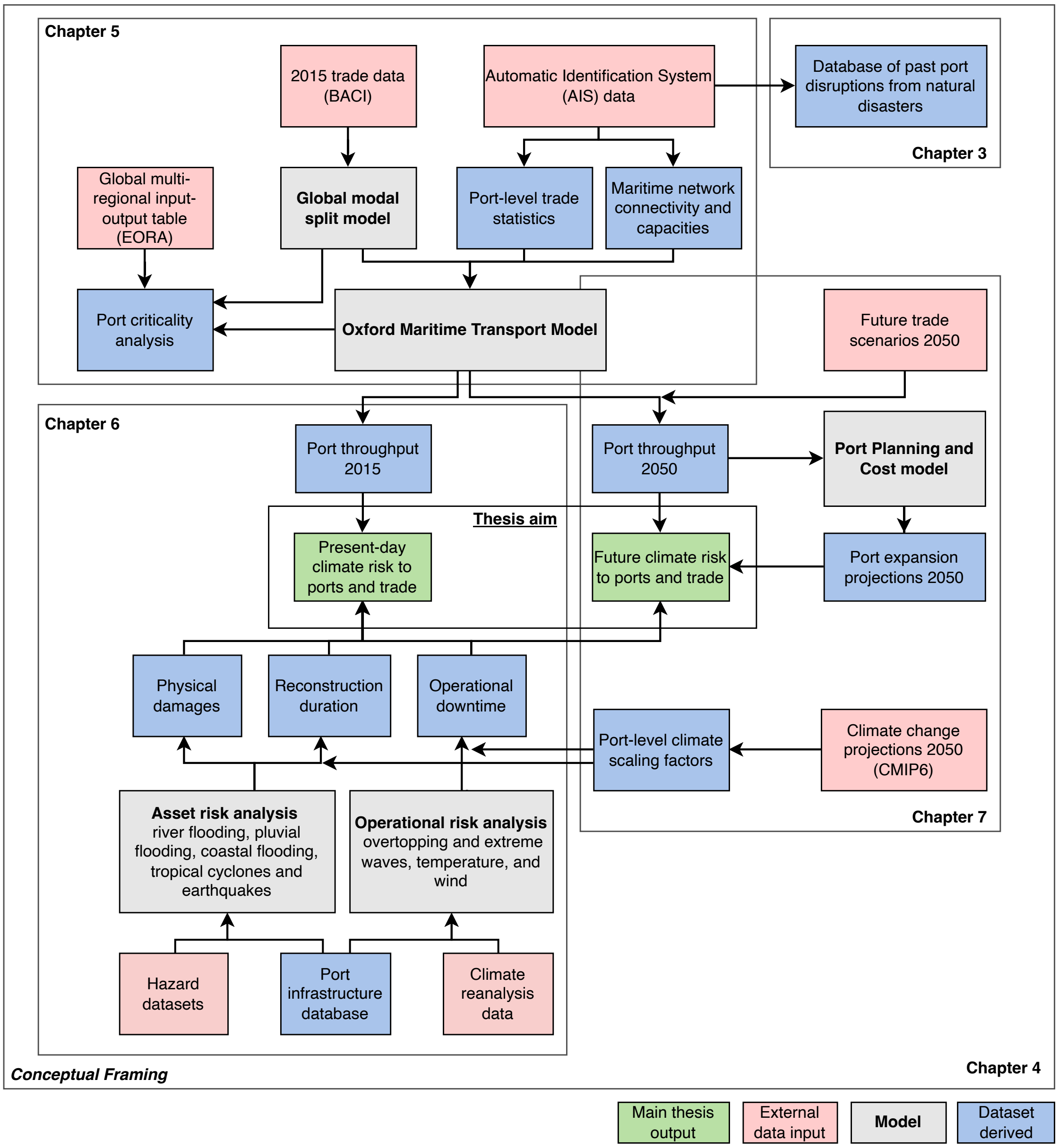

Figure 1.3: Thesis structure, model and data overview, and chapter interconnections.

2 LITERATURE REVIEW

2.1 Climate risks to ports

A disaster is defined by the United Nations Office for Disaster Risk Reduction (UNDRR) as "*a serious disruption of the functioning of a community, a system, or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to human, material, economic or environmental losses and impacts*" (UNDRR, 2022). Relatedly, disaster or climate risk is commonly defined as the interaction of hazard (i.e. the likelihood of a hazard occurring), exposure (i.e. the people, infrastructure, housing, and other tangible human assets located in hazard-prone areas) and vulnerability (i.e. the conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, asset or system to the impacts of hazards) (UNDRR, 2022). Climate or disaster risk often refers to the (direct) physical damages or losses to a specific hazard-prone region, with the scope of this thesis the port infrastructure and operations.

On top of the climate risk to ports, given the interconnected nature of ports within maritime transport, hinterland transport and global economic networks, disruptions to ports could spill over to other (initially unaffected) parts of the network. These are so-called systemic risks, referring to "*the potential knock-on effects to initially unaffected components of a system because of system interactions or dependencies*" (UNDRR, 2022).

Port infrastructure and operations are susceptible to a large variety of climate extremes and natural disasters given the strategic location of ports in low-lying coastal and riverine areas, ranging from yearly occurring extreme weather events (e.g. extremes winds and waves) to low-probability but high-impact natural disaster events (e.g. earthquakes, flooding) (see Figure 2.1 for an overview) (Becker *et al*., 2013; Ng *et al*., 2015).

Climate change poses several challenges to the design, operations and planning of present and future port infrastructure. First, climate change is expected to change the frequency and magnitude of hazard impacts to port infrastructure and operations, requiring adaptation and additional budgets for recovery and reconstruction efforts. Second, given the long lifetime of port infrastructure (50 – 100 years), port planners and engineers face the challenge of having to design infrastructure that should withstand future (uncertain) environmental boundary conditions. Third, ports rely on shipping, inland transport, and other critical infrastructure (e.g. water, energy, telecommunication) networks, which are similarly vulnerable to climate impacts (see Figure 2.1). Fourth, the climate mitigation measures adopted by countries to achieve their emissions targets will shape future trade flows, in particular the trade of energy-related goods, which could significantly impact cargo flows going in and out of ports (Walsh *et al*., 2019).

Given the growing threats to port infrastructure and operations, which can cause damages, downtime and spill-over effects, risks need to be quantified. Risk analyses, quantifying the potential range of losses to ports and those depending on the well-functioning of ports (e.g. carriers, shippers, firms), are therefore needed to understand the overall challenge that maritime actors face and how risks are expected to change in the future. Moreover, it provides the foundation for evaluating the benefits of various adaptation or resilience strategies.

The literature review presented below covers the scientific literature related to the climate risks to ports that underpins the research presented this thesis, and includes an overview of (i) empirical evidence of past port disruptions, (ii) existing risk analyses performed for ports, maritime transport and the economy, and (iii) existing insights into climate change adaptation needs and practises of ports. Every section is followed by a brief summary of the key knowledge gaps identified in the literature.

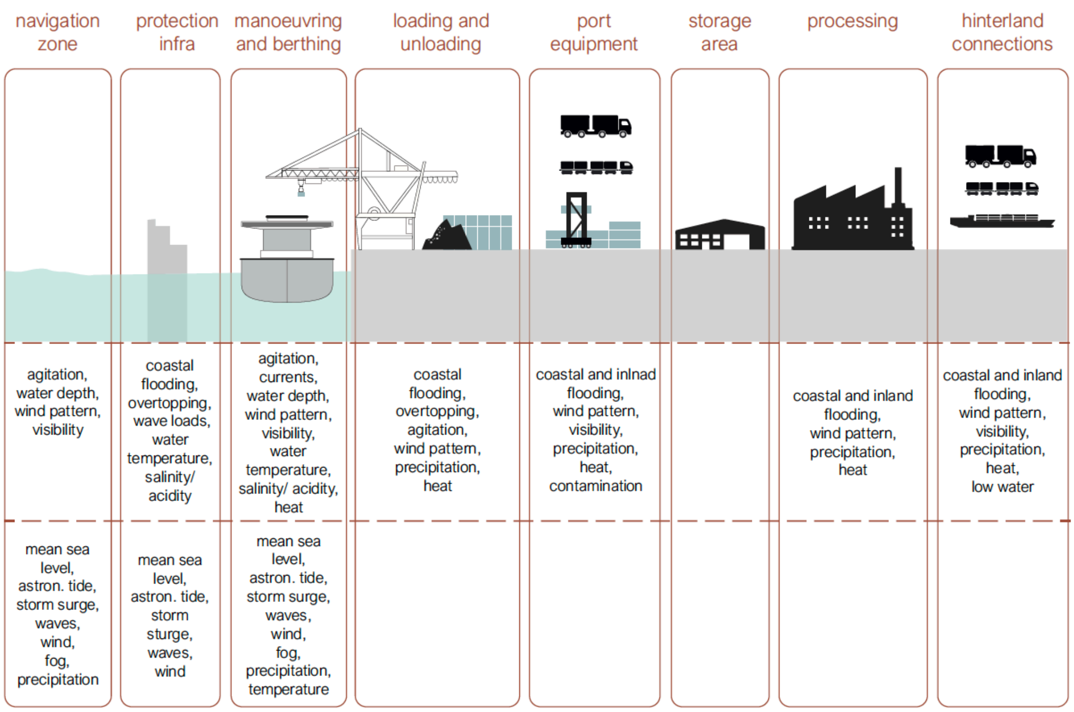

Figure 2.1: The impacts of climate extremes and climate change on different components of port operations at the seaside, quayside and landside. Source: (PIANC, 2020).

2.2 Empirical evidence of port disruptions

Several studies have looked at the past occurrence of port disruptions due to natural disasters and extreme weather events, but also other type of disruptions (mechanical failure, labour strike, political instability, collision). The studies can be grouped into (i) surveys inferring port authorities' past experiences with natural disasters and climate extremes, (ii) the construction of various port disruption databases, and (iii) those using empirical vessel movement data to analysis specific port disruptions.

2.2.1 Port surveys and disruption databases

In 2017, the UNCTAD distributed a survey to 44 port authorities, collecting information on climatic and weather-related impacts to their port facilities (UNCTAD, 2017a). 72% of the surveyed ports reported that they had been impacted by climatic or weather-related extremes in the past, 50% of ports reporting some or significant physical damages and 75% of ports reported some or significant impacts to operations. Extreme winds, precipitation and storm surges were most frequently reported as the climatic extreme that caused disruptions, followed by fog and wave penetration. This survey did not collect information on the duration of the disruptions, making it hard to distinguish the severity of the impacts.

In the past, several studies have constructed databases on the severity (e.g. duration) of port disruptions, some of which focused on natural hazards only, while others on a variety of disruption-triggering events (e.g. labour strikes, mechanical failure, collision, political unrest). For instance, Trepte and Rice collected data on 28 incidences of port disruptions between 2004 and 2010 for United States ports (from all kinds of hazard), showing that the median disruption duration equalled three days with a standard deviation of six days (Trepte and Rice, 2014). Lam and Su discussed 15 disruptions between 2001 and 2011 in Asia, including seven natural hazards, with closure durations ranging from one to 91 days (i.e. Typhoon Maemi affecting Busan) (Lam and Su, 2015). Adam *et al.* elaborated on maritime disruptions in the United Kingdom that took place between 1950 and 2014, identifying 88 events of which 48% were caused by extreme wind or storm surges. Interestingly, the reported events showed an increase in wind-induced port disruptions, while disruptions associated with storm surges have decreased (Adam *et al.*, 2016). Other have focused on providing detailed accounts of port disruptions for specific ports. For instance, an analysis of four Chinese ports (Shanghai, Ningbo, Shenzhen, Guangzhou) showed that typhoons disrupt port operations on average two to seven days per year between 2007 and 2017 (Y. Zhang *et al.*, 2020). Similarly, an analysis of weather-related disruptions between 2013 and 2017 for the Port of Shenzhen highlighted that the month of March has an average monthly downtime of seven days, mainly associated with fog, whereas the months of July and August have an average monthly downtime of around four days due to typhoons and extreme rain (Cao and Lam, 2019). However, the definition of disruption across these studies is unclear, in particular whether this refers to a full shutdown of the port or any type of operational disruption, including minor ones. In other words, the operational dynamics are not captured in these high-level disruption databases.

2.2.2 Empirical insights into port disruption dynamics

To bridge this gap, a small numbers of studies have explored the use of vessel movement data to empirically analyse the operational dynamics of ports before, during and after natural disasters (Farhadi *et al.*, 2016; Touzinsky *et al.*, 2018). Studies have done such analysis for the port of New York/New Jersey during Hurricane Sandy (2012) (Farhadi *et al*., 2016), the ports of Savannah, Charleston and Jacksonville during Hurricane Matthew (2016) (Touzinsky *et al.*, 2018) (see Figure 2.2), the port of New Orleans after Hurricane Katrina (2007), and the port of Kobe after the Hanshin earthquake (1995) (Rousset and Ducruet, 2020). These analyses showed how the operational dynamics of ports follow a behaviour representing a classical resilience curve consisting of the initial shock, a recovery phase and an adaptation phase (Linkov *et al*., 2014) (Figure 2.2). Still, difference can be observed between events and ports. For instance, ports affected by Hurricane Matthew and Sandy recovered relatively quickly (i.e. days or weeks), the impacts of Hurricane Katrina to the port of New Orleans resulted in full recovery after around three to four months (Rousset and Ducruet, 2020), while port traffic at the port of Kobe never returned back to normal (even after 1.5 years) as a result of container flows being relocated to other transhipment ports in the region (Rousset and Ducruet, 2020).

The differences in the operational dynamics thus illustrate how the resilience of ports can differ considerably between events. Similarly, the operational thresholds that cause port operations or infrastructure to be affected differ across ports, as captured in the UNCTAD survey (UNCTAD, 2017a). While most ports reported precipitation thresholds of 0 - 100 mm per day, others reported that equipment could cope with 100 – 200 mm per day or more. Similarly, wind speeds of 50 – 100 km per hour were most frequently reported as operational threshold, although some ports reported that equipment and infrastructure could cope with wind speeds of 100 – 150 km per hour. In terms of the storm surge threshold, ports were even more divided, with reported critical threshold values ranging from one to seven metre, with the largest number of ports reporting either three metre or five metre. The latter likely reflects that terminal deck heights, which determine the exposure to storm surges, can vary more widely as it depends on the local storm surge conditions, the modernity of the port terminal (newer ports are often higher) and the size of the vessels that are calling at the port (larger vessels require higher terminal decks).

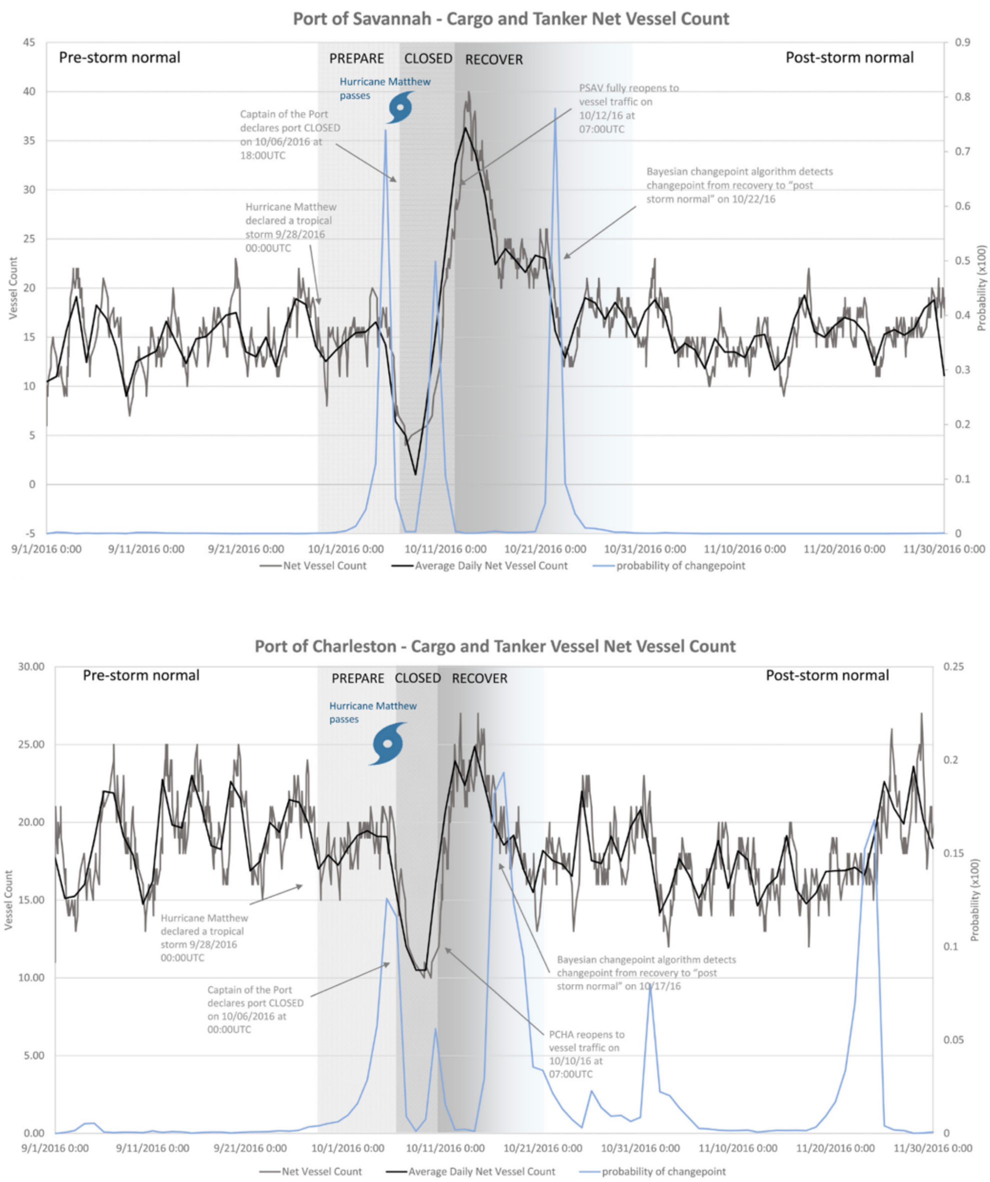

Figure 2.2: Vessel count before, during and after Hurricane Matthew (2016) as derived from Automatic Identification System data (Touzinsky *et al.*, 2018).

2.2.3 Summary empirical evidence port disruptions

The empirical evidence of port disruptions suggest that the vast majority of ports face annual disruptions due to extreme weather events, with the rare occurrence of natural disasters having the potential to shut down a port for weeks or even months. However, the extent of the disruption largely varies according to the type of event, magnitude, and port, making it hard to generalise the results. Hence, alongside information on the disruption duration of past event, insights into the factors that drive the resilience of the affected ports are essential. While several studies have analysed the operational resilience of ports using empirical vessel data for a handful of events, particularly in the United States, this has not yet been expanded to other regions, although the methodology used provides a generic way to analyse port disruptions across countries.

2.3 Risk analysis to ports, maritime transport and the economy

Risk analysis aims to quantify the (climate) risks to the system under consideration, which can help identify and prioritise options to reduce risk. In general, a risk analysis to ports follows a workflow as shown in Figure 2.3, which includes (i) identifying the climate and non-climatic drivers that can impact a port, (ii) identifying port vulnerabilities and future risk factors, (iii) analysing and evaluating risks by combining the likelihood of the event with the modelled consequences, and (iv) identifying and prioritising suitable adaptation options to reduce present and future risk.

Different types of risk analyses have been performed to evaluate physical damages to port infrastructure or the expected losses as a result of port downtime (e.g. revenue losses).

These studies can broadly be grouped according to the spatial scale and the type of impacts considered; (i) those focusing on port-level impact analysis, either detailed local analysis or coarser large-scale exposure analysis, (ii) those looking at maritime networks and the potential system-wide disruption, and (iii) those focusing on the macroeconomic implications of port disruptions.

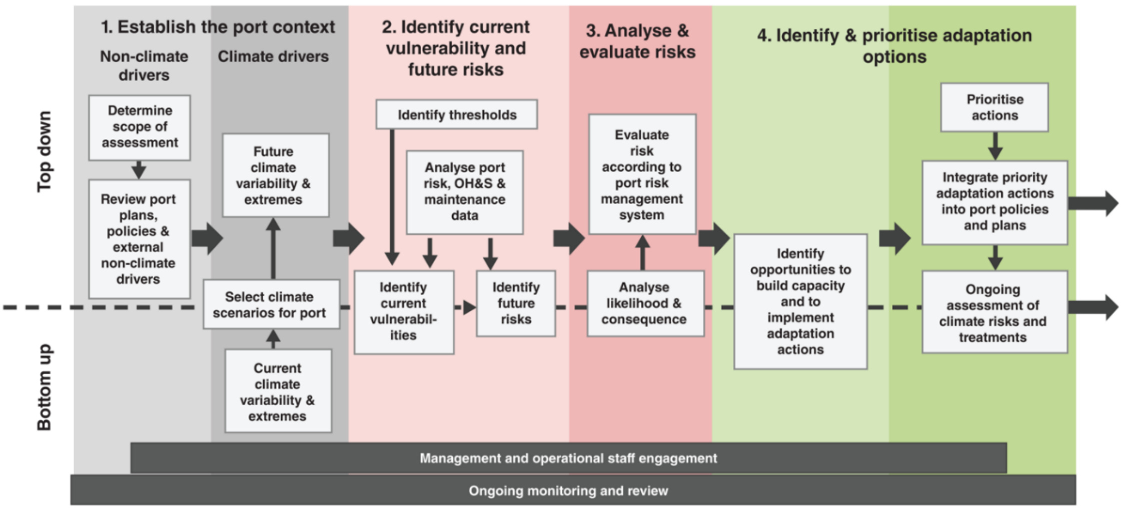

Figure 2.3: Overview of a climate risk assessment process for ports (McEvoy and Mullett, 2013).

2.3.1 Port-level impact analyses

Various impact analyses of individual ports, or a subset of ports on a regional scale, have been performed. Risk to ports can either be expressed as the annual expected physical damages to port assets (e.g. terminals, cranes, warehouses), which reflect the reconstruction costs of these assets, or the annual expected downtime of port operations, which, when multiplied with the daily throughput, could yield the expected annual trade at risk or revenue losses.

On a local-scale (that is on a detailed port-level), a large and growing number of studies have analysed the operational downtime of a port for a specific hazard, such as tropical cyclones and extreme winds (Esteban, Webersik and Shibayama, 2010; Zhang and Lam, 2015; Esteban, Takagi and Shibayama, 2016; Cao and Lam, 2019), extreme water levels (Bove *et al.*, 2020; Jebbad *et al.*, 2022), wave penetration inside the port boundary (Sierra *et al*., 2017; Camus *et al*., 2019), or the overtopping of breakwaters (Sierra *et al*., 2016; Sierra, 2019). In most cases, these studies evaluate how climate change could modify the operational downtime in the future. For instance, Esteban *et al*. quantified the change in typhoon-induced downtime for major Japanese ports, finding that a 10% increase in typhoon intensity can increase downtime by around 20 – 40% by 2085 (Esteban, Webersik and Shibayama, 2010). Camus *et al.* studied the operational downtime as a result of wave penetration into the harbour area of the port of Candás (northern Spain) and how this might change in the future under climate change (due to changing wave height, wave period and storm surges), showing that operational downtime could increase by a factor 1.4 to 2.0 in 2100 compared the present-day situation (2010) (Camus *et al*., 2019).

The physical asset damages to specific infrastructure within the port area has received considerable less attention. Pitilakis *et al*., for instance, presented a detailed asset-level risk analysis to quay walls, buildings, cranes, warehouses and electricity infrastructure located in the port of Thessaloniki (Greece), evaluating the risks from both (tsunami-induced) flooding and earthquakes (Pitilakis *et al*., 2019). Abdelhafez *et al*. studied the flood inundation impacts to port assets and operations from Hurricane Katrina for the port of Mobile (United States), including how this might change under different sea-level rise scenarios (RCP4.5 and RCP8.5) and an alternative hurricane track (Abdelhafez, Ellingwood and Mahmoud, 2021). They found that physical asset damages could increase by a factor 5.5 – 7 by 2100. Additionally, the port could experience a 65% decrease in overall functionality under a RCP4.5 scenario and could become complete inoperable under a RCP8.5 scenario. In previous analyses, considerably less attention is given to the risk to critical infrastructure assets outside the port boundary that ports rely on (e.g. roads, rail, electricity, telecom). For instance, an analysis of the exposure of four United States East Coast container terminals to sea-level rise illustrated that while a high-end sea-level rise scenario for 2100 might cause frequent nuisance flooding at low-lying terminals, the most severe impacts are projected to occur at certain major roads that feed these port terminals (Allen, McLeod and Hutt, 2021). A similar result was found for a detailed analysis of the consequences of sea-level rise for the port of Los Angeles and Long Beach (Aerts *et al.*, 2018).

On a regional or global scale, various studies have analysed the exposure of ports, either for a specific hazard or multiple hazards. While local scale studies often consider the spatial outline of the port infrastructure, larger scale studies consider ports as single point locations. For instance, the present-day exposure of 68 Caribbean ports to various natural hazards (six types of natural disasters) was considered, finding that around 60% of ports are exposed to hurricane wind and earthquakes, while flood exposure is considered low (Rozenberg *et al*., 2021). In this study, the exceedance of operation thresholds were not considered, nor the future changes in the exposure levels. However, A study of 44 Caribbean ports found that 80% of ports would experience flooding given one metre of sea-level rise without adaptive measures (Simpson *et al*., 2010), a result confirmed for a more fine-scaled analysis in the United States Virgin Islands, Jamaica and St. Lucia (Monioudi *et al.*, 2018; Bove *et al.*, 2020). Similarly, another study evaluated the exposure of ports in Europe to coastal flooding at present and in the future (2100) (Christodoulou, Christidis and Demirel, 2019), in which they quantified the cargo tonnage exposed to extreme water-levels associated with a 1-in-100 year event (not the inundation). At present, around 96 ports are exposed to >4.5 metre thresholds (out of 1428 ports), while in 2100 this number could increase by an additional 29 ports under RCP4.5 and 40 ports under RCP8.5. Similarly, the cargo exposed could increases by 10% under RCP4.5 and 13% under RCP8.5. Only one study monetised (some of) the expected impacts to infrastructure assets using a cyclone risk model for 14 East Asian container ports (Jian, Liu and Lam, 2019). A 1-in-100-year cyclone wind could incur 10 to 90 USD million in physical asset damages, while storm surge could cause damages worth 10 to 600 USD million.

So far, only one study has performed a global analysis, modelling the disruptions to port operations from six climatic extremes (e.g. wind, waves, overtopping, extreme water levels, high temperature, precipitation) on a global scale, including the evolution of this exposure into the future under one climate scenario (RCP8.5 for 2100) (Izaguirre *et al.*, 2021). This study found that 42% of ports are exposed to all operational extremes (see Figure 2.4), located mainly in East Asia and the Pacific. At present, the largest operational disruptions are faced by ports in cyclone-prone areas, while in the future the impacts of coastal flooding, overtopping and high temperature could cause the largest increase in operational downtime. As a consequences, some areas presently facing limited exposure to operational disruptions, like the Middle-East, India, South-East Asia and parts of Europe, have the potential to face more frequent operational disruptions in the future (Figure 2.4). However, the economic implications of these disruptions in terms of port downtime or trade at risk was not considered in this study, making it hard to quantify the (monetised) risk of ports and the need for adaptation.

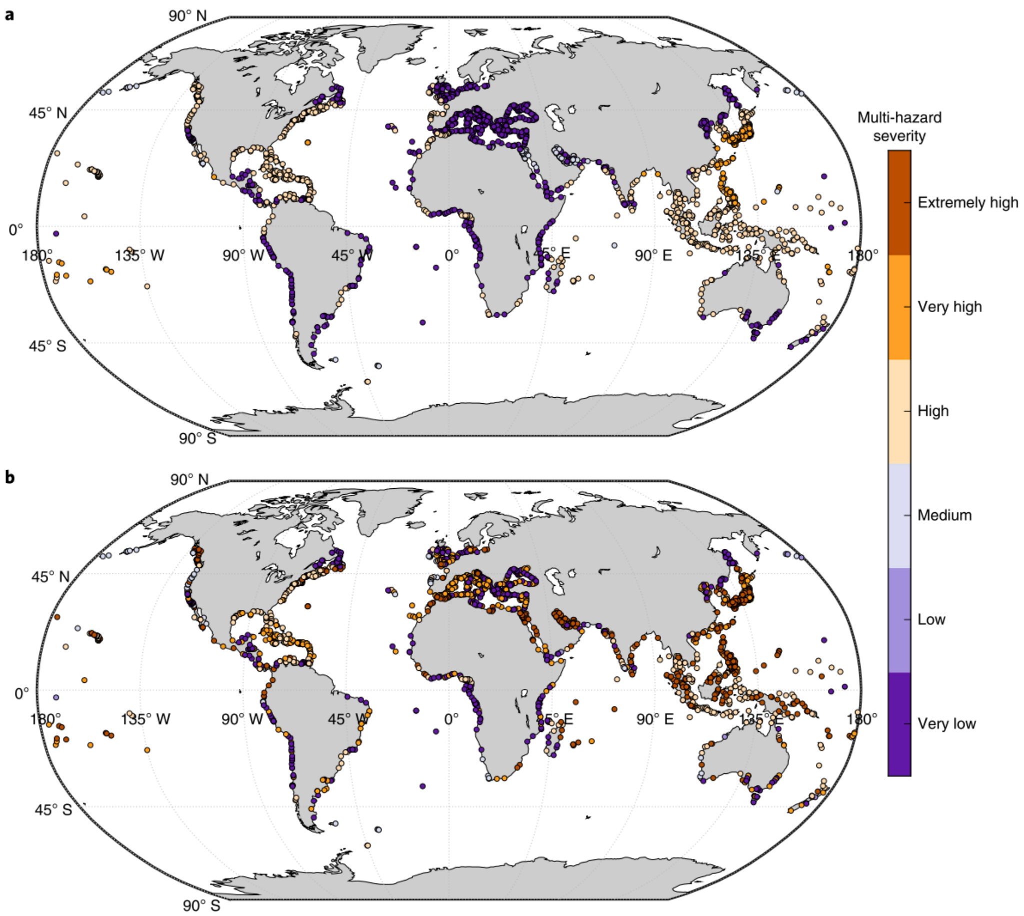

Figure 2.4: Multi-hazard severity of ports due to the exceedance of operational thresholds. Top panel depicts the present-day situation while the bottom panel depicts the future situation in 2100 under RCP8.5 (Izaguirre *et al*., 2021).

2.3.2 Summary port impact analysis

In summary, a couple of general observations can be made. Detailed port-specific case studies often estimate the physical asset risk or operational downtime for a given hazard type, including evaluating how this might change in the future. This is often done using a combination of the asset representation of port terminals and breakwaters, and a detailed hazard model (e.g. hydrodynamic model). However, only a handful of studies try to scale this up to a regional or global scale, and if they do, these studies have major limitations. First, ports are represented as single point locations instead of a detailed spatial representation of the port assets, which, given the large size of certain ports, can matter significantly for the risk analysis. Similarly, limited attention is given to the risks to other critical infrastructure in the vicinity of the port (roads, railways, electricity) that are essential for the well-functioning of ports. Second, in almost all cases, only the exposure is quantified, that is whether or not a port (point) is exposed to a specific type of event (e.g. a 1-in-100 year event), and not the full range of probable events. Third, while studies have looked at the exposure of natural disasters and operational thresholds separately, no study has evaluated both of them in a single framework. Given that these hazards cover both ends of the risk spectrum (e.g. low-probability but high-impact and high-probability but low-impact events), comparing and contrasting the risks in a single framework is imperative. Fourth, and most importantly, only very limited studies have tried to quantify the consequences of hazard impact in terms of asset damages or the exceedance of operational thresholds for a large number of ports. Quantifying the physical asset damages is limited by the fact that no global asset database of ports exist, while quantifying the amount of trade disrupted is limited by a lack of information on the flow of goods through ports globally.

2.3.3 Maritime transport impact analyses

When ports are disrupted, other components of the maritime transport network could also be impaired. Several studies have performed a system-wide analysis of the maritime transport network to identify such vulnerabilities. These studies distinguish themselves by focusing on the systemic vulnerabilities and impacts and as a result of a port disruption, including maritime transport network spill-overs, the losses to various actors in the maritime logistics chain (e.g. shippers, terminal operators, carriers), and the resilience of transport system (e.g. rerouting).

An increasingly large number of studies have analysed the network characteristics of the maritime transport network by creating a graph representation of the nodes (ports) and edges (maritime links) of the system (Kaluza *et al*., 2010; Ducruet, 2016; Lhomme, 2016; Viljoen and Joubert, 2016; Calatayud, Mangan and Palacin, 2017; Peng *et al*., 2018; Kosowska-Stamirowska, 2020; Xu *et al*., 2020). Viljoen and Joubert (2016), for instance, found that the maritime transport network is robust against targeted attacks, which captures how the network loses connectivity after removing a port from the network. Similarly, Calatayud *et al*. emphasised that the hub and spoke system of maritime connections (with hub ports responsible for connecting ports without direct connection with each another) shape the vulnerability of the system in North and South America, in particular the subnetworks of different shipping lines (Calatayud, Mangan and Palacin, 2017). Ducruet analysed the vulnerability of the maritime transport network to a disruption of the Suez and Panama Canal, finding that ports in Asia, Europe and North America are critically dependent on the functioning of the canals, and could be easily cut-off from major parts of the global network in case of a disruption (Ducruet, 2016).

These network-based studies suffer two major limitations. First, while they represent the network connectivity, the actual flows on the network are not considered, and often network edges are considered binary (or unweighted). Second, 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 empirical evidence of real world network disruptions exist, given a lack of data, including an understanding of the mechanisms which govern network re-organisation during and after disruptions. Kosowska-Stamirowska did empirically investigate the network re-organisation after 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 (Kosowska-Stamirowska, 2020). Similarly, Rousset and Ducruet showed that rerouting took places after Hurricane Katrina (affecting New Orleans) and the Hansin Earthquake (affecting Kobe) (Rousset and Ducruet, 2020).

Alternatively, (often national) models are developed to simulate the freight (re-) assignment in case of port disruptions using freight modelling (Jones *et al.*, 2011) or a more empirical/statistical approach (Paul and Maloni, 2010; Akakura *et al.*, 2015), quantifying the amount of freight that can be rerouted and the fraction of freight lost (i.e. freight that could not be re-allocated) in case of a disruption. For instance, Akakura *et al.* evaluated the benefits of temporarily ramping up capacity in unaffected Japanese ports to divert cargo flows after an earthquake disrupting ports in Northern Japan for a certain amount of time. They found significant potential of alternative ports to handle disrupted flows (up to 90%), although critically dependent on the number and selection of ports being out of service. While these models allow simulating the optimal diversion routes of disrupted cargo (in an aggregate sense), they are often static and do not provide a simulation of the dynamic re-assignment (on a vessel-by-vessel basis), including port and network capacity constraints, over time.

To better capture how the maritime transport network can cope with and adapt to network perturbations, several studies have constructed detailed liner assignment models that can be used to simulate vessel rerouting as a result of port or route disruptions, and the associated costs of rerouting (Li, Qi and Lee, 2015; Novati *et al.*, 2015; Achurra-

Gonzalez, Angeloudis, *et al.*, 2019). For instance, Achurra-Gonzalez *et al*. evaluated how the degree of cargo diversion between the six main ports in the Le Havre-Hamburg range influences the costs associated with cargo disruption (e.g. cost of rerouting and penalty cost of not delivering containers) (Achurra-Gonzalez, Angeloudis, *et al.*, 2019). This study showed 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 (Figure 2.5). 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 (see Figure 2.5). However, for larger disruptions and low cargo diversion, disruption costs quickly accumulate. Although these models help in the quantification of the costs associated port downtime, 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 maritime transport network.

Beyond the cost of rerouting or delays, other economic losses to various actors involved in the maritime logistics chain are hardly considered in previous analysis. Only two studies (Zhang and Lam, 2015; Y. Zhang *et al.*, 2020), focusing on port disruptions to four Chinese ports as a result of cyclone-induced extreme winds, considered other losses to various logistics actors, including the loss to shippers (inventory costs and depreciation), carriers (loss of income for not delivering goods) and terminal operators (loss of revenue from loading and unloading goods). This loss is a function of both the throughput that is disrupted and the annual frequency of occurrence of extreme winds. For Shanghai and Ningbo ports, this loss is in the order of 100 USD million per year, while for the port of Shenzhen this is close to 300 USD million per year, showing that these losses can be substantial and should be quantified.

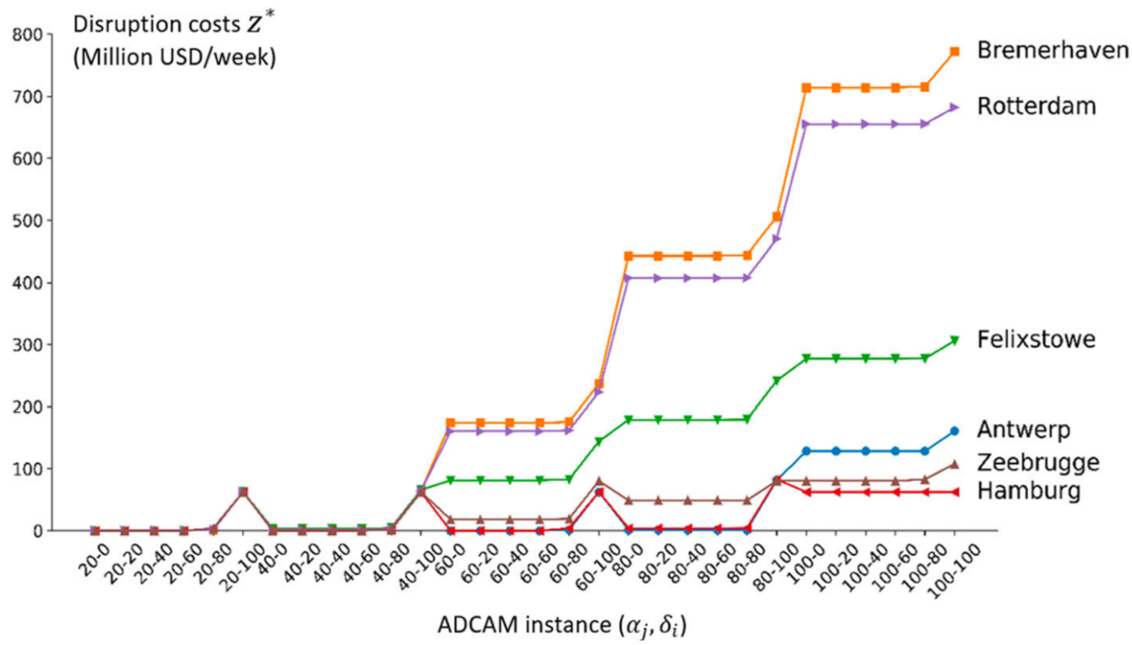

Figure 2.5: The disruption costs (cost of rerouting and penalty for non-delivery) associated with different combinations of the attacker-defender model setup. Alpha reflects the capacity disrupted by the attacked (0 to 100%), while delta is the percentage of flow that can be diverted (0 to 100%) (Achurra-Gonzalez, Angeloudis, *et al.*, 2019).

2.3.4 Summary maritime transport impact analysis

An overview of the literature focusing on the implications of port disruptions to the national, regional and global maritime transport system highlights a wide range of different modelling approaches, all with benefits and drawbacks. Specifically, network-based disruption analyses, using targeted or random attacks, provide insights in the overall network characteristics, but do not consider actual freight flows, ignore any form of network resilience, and do not quantify the likelihood of such port failures. As such, they are constrained in quantifying the economic losses associated with network failures.

On the other hand, detailed simulation-based approaches are designed to predict the dynamic re-alignment of freight flows using an optimisation algorithm, and the associated costs of delays and rerouting. However, given the data needs and computational complexity, they can realistically only represent regional transport networks, and losses to other actors in the maritime logistics chain are ignored, such as losses to shippers, carriers and terminal operations. Hence, at present, there is an apparent mismatch between the scale of the analysis (e.g. regional versus global) and the level of detail of that can be included in terms of loss simulation. A reduced complexity global maritime transport model (Tavasszy *et al.*, 2011; Martínez, Kauppila and Castaing, 2015), that allows simulating the optimal flow allocation under capacity and other constraints is highly desirable for maritime impact analyses, but has not yet been utilised for such purposes.

2.3.5 Economic impact analyses

Apart from spill-overs within the maritime transport network, economies that directly or indirectly depend on a port for its trade may suffer losses. A number of studies have evaluated the macroeconomic impacts of port disruptions. Such studies typically combine disruption scenarios (e.g. number of days of downtime) or a port simulation model (e.g. that measures the inoperability of a port over time) in combination with a macroeconomic model (i.e. input-output model, computationally general equilibrium model) to quantify how trade disruptions could result in economic losses to the regional, national or global economy.

Park *et al*. modelled the macroeconomic implications of an 11 day port disruption at the ports of Los Angeles-Long Beach, finding losses of approximately 1.15 USD billion per day, while Jung, Santos and Haimes estimated this to be 0.8 – 1.3 USD million per day (Park *et al*., 2008; Jung, Santos and Haimes, 2009). Rose and Wei evaluated the macroeconomic implications of a 90-day port disruption at the twin port of Port Arthur and Beaumont. They found that 11 USD billion of trade could be disrupted, resulting in 170 USD billion of wider economic losses, a multiplier of almost 15 (Rose and Wei, 2013). Pant *et al.* looked at a two-week closure of the Port of Catoosa (Oklahoma), showing how 38 USD million in direct trade losses (i.e. import and export flowing through the port) can cause 102 USD million of economic output loss, without considering any type of adaptive capacity of firms (multiplier of 2.7) (Pant *et al*., 2011). Similarly, Wei, Chen and Rose studied a year-long trade disruption (recovering linearly) as a result of a tsunami affecting the ports of Los Angeles and Long Beach. The 200 USD billion of trade being disrupted could amplify to 570 USD billion of disrupted economic output (multiplier of ~2.9) to the USA economy (or 3.1 USD billion per day) (Wei, Chen and Rose, 2020). A similar model set-up was used to analyse the impacts of a severe earthquake occurring at the same port (Wei *et al.*, 2022), but this study made methodological advances in explicitly modelling the operational downtime to port facilities due to earthquake damage and the resulting repair time. Apart from the 210 USD million of repair and reconstruction costs, the earthquake, which reduced operations by around 40-50% and takes around 150 days to recover from (reconstruction of assets), could lead to macroeconomic losses of up to 11 USD billion to the national economy. The latter underlines how macroeconomic losses, even if not all materialising, could be considerably higher than the repair and reconstruction costs associated with the direct physical damages.

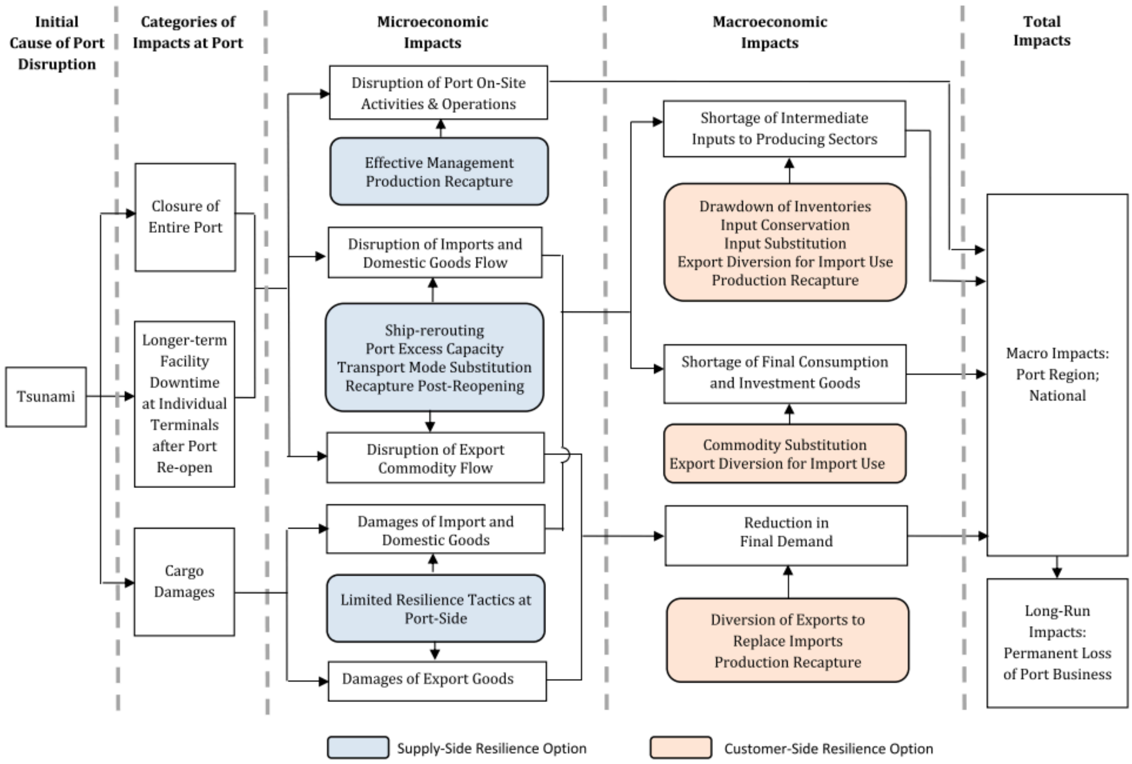

Figure 2.6: Overview of the macroeconomic impact framework to model the wider economic losses of port disruptions. The blue and orange components include various supply-side and customer-side resilience options embedded in the model (Wei, Chen and Rose, 2020).

These reported macroeconomic losses are considered an overestimation of the likely impacts, as they assume that trade is completely lost, and no port, logistics or firm-level resilience options are implemented. These resilience options can be incorporated in the model in different ways (see Figure 2.6), at both the supply and customer side, and have the potential to significantly reduce the modelled losses. For instance, implementing resilience options at the (port) supply side (e.g. rerouting, production recapture, inventories) can reduce the losses by 4 – 58% for the ports of Los Angeles-Long Beach (Wei, Chen and Rose, 2020; Wei *et al.*, 2022), while combining supply-side resilience options with customer resilience (e.g. input substitution, import substitution) could reduce losses by almost 99%. Nonetheless, the aforementioned case studies only consider the impacts to the USA national economy, ignoring international spill-overs or the fact that other countries are partly able to buffer the economic impacts. For example, Koks and Thissen assessed the European-wide macroeconomic losses as a result of a large-scale flood event affecting the port of Rotterdam area (in particular the industry cluster in the port) (Koks and Thissen, 2016). They found that the European manufacturing hubs in Germany, France and northern Italy would incur large losses, while other regions could partly buffer the losses as they take over production from the affected region. Kuhla *et al.* are the first to model the macroeconomic losses of maritime disruptions on a global scale. By combining 21 years of typhoon tracks in the East Asian region with an agent-based macroeconomic impact model (Acclimate), they studied the impacts of maritime transport route disruptions (so not ports) to the global economy (Kuhla *et al*., 2022). On the one hand, the way the maritime transport network is embedded within the modelling framework is simplified, given the limited number of ports, lack of information on maritime connectivity, specialisation and capacity constraints, and the fact that the share of trade using aviation is not subtracted (transporting 30-35% of global trade in value). On the other hand, the representation of transit times and firm behaviour to cope with transport delays is a significant improvement compared to other studies, as it captures that trade is not directly lost and other (unaffected) economies are able to temporarily supply disrupted trade. This study found that typhoons usually disrupt Asian shipping routes for 1 to 8 days, depending on the trajectory, with countries that trade with each other in the region experiencing the largest losses. Nonetheless, exports from East-Asia, Europe and North America could benefit from frequent transport disruptions as they will substitute production.

2.3.6 Summary economic impact analyses

Altogether, a number of studies have performed detailed analyses of the macroeconomic losses as a result of port disruptions, in particular for the United States. However, scaling such analysis up to other countries or the global scale, as well as extending the analysis from a scenario-analysis to a risk analysis, is challenging for several reasons. First, to enable coupling an input-output table with the trade flows through a specific port, information on sector-specific trade flows (in value terms) going in and out of a port is required. This type of information is not readily available except for a few countries (as most port authorities only report aggregate throughput in quantity terms). Second, even if countries have information on the share of imports and exports flowing through a particular port, information where this trade is coming from or is going to is not reported, making it hard to model international trade spill-overs. Third, most aforementioned studies have used scenario analysis to inform the disruption duration, without specifying the likelihood of certain disruptions. Similarly, apart from Wei *et al.*, most studies do not actually model the damages to port facilities as a result of natural disasters or climate extremes (Wei *et al.*, 2022). Hence, end-to-end impact analysis, combining detailed climate risk analysis to port infrastructure with a macroeconomic modelling framework remains unexplored.

2.4 Climate adaptation in practise

As ports are at the forefront of climate change, adaptation is inevitable. Apart from an increasing risk associated with climate change, the expansion of port areas also places more infrastructure at risk. For instance, as a result of socio-economic growth, global maritime trade is expected to nearly triple by 2050 compared to 2015 (ITF, 2015; Walsh *et al*., 2019), with country-level estimates showing that around 2500 - 5000 km^2 of new port terminal are needed between 2010 and 2050 (Hanson and Nicholls, 2020).

Broadly speaking, three types of adaptation strategies can be considered to adapt ports; accommodate, defend or retreat (Aerts *et al*., 2014). Accommodating port facilities is the most widely discussed adaptation option, which entails elevating port terminals to a new design level. Defending a port captures the construction of coastal or riverine protection infrastructure, such as breakwaters, embankments, flood walls or locks (Becker *et al*., 2016). At least, port retreat encompasses a complete relocation of existing port facilities, which is an unlikely option in many places given the lack of available land or societal dependence on port areas. Alternatively, it would mean the reallocation of port activity from one port to another.

Climate adaptation necessitates looking 30 to 100 years ahead, which is often misaligned with the traditional port planning cycles. Generally speaking, four generic port planning types can be identified (Dooms and Verbeke, 2006; Van Koningsveld *et al*., 2021):

- Operational planning (1 – 3 years);
- Short-term strategic planning (~5 years), which focuses on commercial, marketing and financial goals;
- Port master planning (10 – 15 years), characterised by a detailed action plan to build new or upgrade existing port infrastructure with high degree of site specificity;
- Longer-term strategic planning (~25 years), which aims at formulating and evaluating longer-term port expansions trajectories with generally a low degree of site specificity.

Even within the time frame of longer-term strategic planning, uncertainties with respect to climate makes deterministic planning difficult. First of all, from the project outlines up to the point that the engineering designs are done and the infrastructure is constructed, boundary conditions may have changed. More importantly, the service lifetime of port infrastructure could be 50 - 100 years. In the era of climate change, this means that only looking at past observations for planning and design might lead to large underestimations in terms of required engineering design and the expected downtime of a port. This misalignment of timeframes is visualised in Figure 2.7.

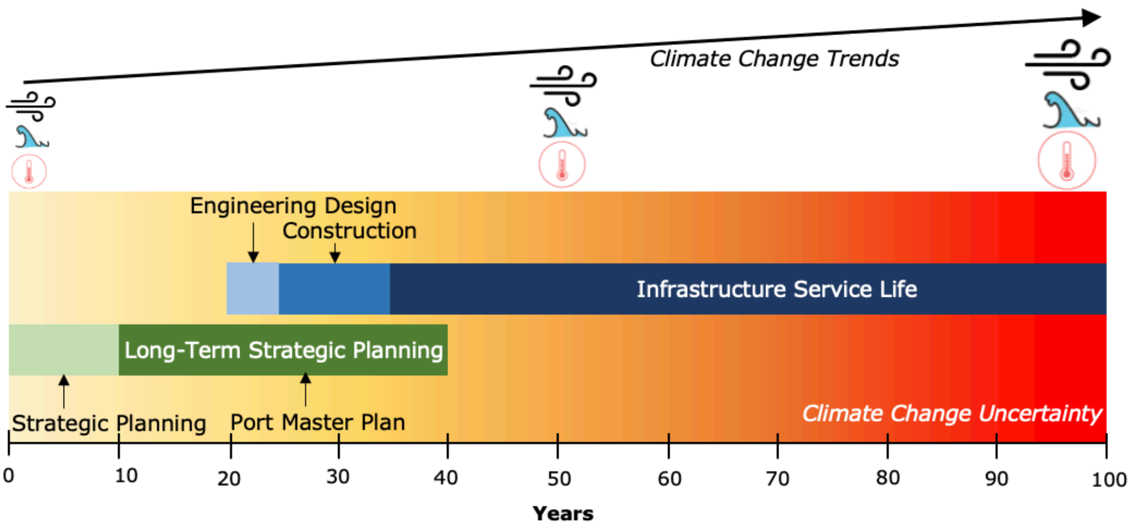

Figure 2.7: Overview of the climate change trends and uncertainty with respect to the long-term strategic planning of ports, including the service lifetime of infrastructure.

The literature on port adaptation is split in two categories; (i) modelling studies intending to quantify the adaptation needs and associated costs, and (ii) surveys with port authorities and engineers to outline the current level of adaptation practises and limits.

2.5 Quantifying adaptation needs

Adaptation needs are defined as the required action to ensure the integrity of port assets and operations as a result of anticipated changes in risk due to climate change. Most of the existing literature on port adaptation has focused on the elevate and defend strategies, mainly in terms of estimating the costs and material needs.

2.5.1 Elevate strategy

Elevating ports implies artificially raising the port terminals, or part of them. For instance, one study estimated the materials costs to raise low-lying port areas for three ports in Japan (Tokyo, Kawasaki, Yokohama) to cope with a typhoon and 1.9 metre of sea-level rise, finding that raising 38 km^2 of port area would require almost 300 billion yen (~2.2 USD billion) (Esteban, Takagi and Shibayama, 2016). This number, however, does not include the cost of demolishing and rebuilding port infrastructure, nor adapting existing breakwaters. Becker, Hippe and McLean estimated that the dredged material needed to elevate existing ports in the United States by two metres is equal to four times the total materials dredged in the United States annually, as well as having a cost of 60 – 80 USD billion (including demolishing and reconstruction of buildings and pavements) (Becker, Hippe and Mclean, 2017). The authors found that given the large fixed costs of demolishing and reconstructing infrastructure, the incremental costs of elevating more upfront is relatively little. These findings are aligned with another study that quantified the costs to elevate 53 large ports in the Asia Pacific with 1.6 and 2.3 metre, which are estimated to be between 30 – 50 USD billion (ARE, 2018). In fact, this study quantified that given the high fixed costs to elevate existing terminals, the difference in total costs between the lower and higher sea-level rise scenario is only around 5%.

However, overall little attention in the scholarship is given to the benefits of such adaptation measures in terms of avoided losses, and whether it is worth making the investments. Jebbad *et al.* assessed the implications of sea-level rise on operations at the Tangier-Med port in Morocco (Jebbad *et al*., 2022). They considered both the inoperability of the port (due to exceedance of the minimum freeboard height) and the likelihood of deck flooding under three sea-level rise scenarios. Only under a high-end sea-level rise scenario in 2100 (1.8 metre) does the main container terminal become inoperable, but for 110 days a year, which could disrupt around 2 million TEU of containers and over 22.5 million tons of goods (Jebbad *et al*., 2022). The costs to elevate the port area to prevent inoperability in 2100 is found to be 40 Euro million. In order to evaluate the cost and benefits of such an intervention, the benefits of avoided revenue from inoperability should have been included in the analysis, as well as the likelihood of experiencing different sea-level rise scenarios. Only Sriver *et al.* performed a detailed cost-benefit analysis of the elevation adaptation strategy, including the consideration of various uncertainties (Sriver *et al*., 2018). Using an idealised case study for the Port of Los Angeles, they explored the need to upgrade the container terminal deck given future sea-level rise. Using a robust decision making framework, in which the full probability space of key decision relevant factors was sampled (e.g. lifetime, sea-level rise, maximum allowable overtopping), they found that the expected lifetime of the infrastructure is a major decisive factor. For a 50 year lifetime, there is only a 1% probability that upgrading the terminal would result in a positive cost-benefit ratio, while for a 100 year lifetime this number increases to 15%. This study underlines the need to consider service lifetime instead of project lifetime when evaluating the cost and benefits of infrastructure upgrades or expansions.

2.5.2 Defensive strategies

In terms of defensive adaptation measures, most studies have evaluated the need to retrofit breakwater structures or build new protective infrastructure. Esteban, Takagi and Shibayama estimated the need to retrofit existing breakwaters (both rubble mound and caisson) surrounding ports in the Tokyo Bay area as a result of changing wave height and sea-level rise. They found a large increase in the required armour size of rubble mound breakwaters, in particular in shallow water depths (up to 100% for a 5 metre water depth) (Esteban, Takagi and Shibayama, 2016). Sierra studied the changing risks of overtopping for 47 ports in Spain given climate change (sea-level rise and increased storminess), showing that damages to ports could increase by a factor three (under a 50 year event, which is roughly the design conditions of breakwaters), but only under a very large sea-level rise scenario (1.8 metre by 2100) (Sierra, 2019). The costs of adapting breakwaters, by constructing a crown wall on top of them, ranges from 8 euro million to 18 euro million, depending on the acceptable level of damage and sea-level rise scenario (again for a 50 year return period). Although the costs of adaptation exceed the benefits for most ports, the adaptation costs are a very small component of the total investment costs of breakwaters (e.g. 1%), emphasising that adaptation could be easily embedded within new breakwater designs at relatively low additional cost. The observation of costly adaptation of existing breakwaters is in line with the UNCTAD survey, in which 54% of port authorities indicated that breakwaters could not be upgraded at reasonable cost (UNCTAD, 2017a). Another challenge, as identified by Becker *et al.*, is the extensive materials needs required to adapt seaports, in particular in terms of concrete, quarry stone and sand. They quantified the materials needed to adapt >200 seaports to 2 metre of sea-level rise by constructing new floodwalls (T-Type), rubble mound breakwaters or caisson breakwaters, underlining potential challenges in mobilising such vast amounts of materials (Becker *et al*., 2016).

2.5.3 Other adaptation options

Other types of adaptation options are less often considered in the academic literature, such as cranes that can operate under higher wind speed, raising roads and railways, upgrades to drainage systems, or the construction of wind walls. However, some port specific adaptation studies in the grey literature have considered such options. For instance, for the port of Manzanillo (Mexico), upgrades to the drainage systems, implementing sustainable urban drainage systems (SUDS), and improved tie-down systems of cranes were considered (Canevari *et al*., 2015). In addition, for the port of Cartagena, the cost and benefits of elevating the access road and raising low-lying storage areas was evaluated (Stenek *et al*., 2011). However, given that these solutions are often context-specific, extrapolating these options to a larger scale is difficult.

2.6 Existing adaptation practises

Apart from quantitative studies of the adaptation needs, various surveys have explored the perception of port authorities with respect to their preparedness, existing practises and perceived difficulties of adapting ports to climate change.

2.6.1 Evidence of adaptation planning

A survey of 90 port authorities around the world investigated the degree of preparedness to future sea-level rise (Becker *et al*., 2012). This survey found that capital improvements, expansions, and maintenance works usually adopt a 5 to 10 years planning horizon, with only 17% of port looking more than 25 years ahead. Moreover, two-thirds of port authorities responded that they felt uninformed about climate change. A survey executed by UNCTAD across 44 port authorities showed that 65% of all ports indicated that adaptation will be required because of climate change, while 70% of ports have emergency response measures in place related to climate-related threats (UNCTAD, 2017a). 76% of ports reported that climate extremes are considered in the planning, design and construction of infrastructure. This percentage is in line surveys by Lin *et al*., covering 18 ports in China, and Ng *et al.*, collecting data on 70 ports in Asia and North America, who both found that two-thirds of the ports proactively consider or address climate change (Ng *et al*., 2018; Lin *et al*., 2020).

Even though climate change is often considered in planning of infrastructure, only 25% of surveyed port authorities by Ng *et al*. mentioned that climate change has been addressed as part of the port’s design guidelines. This is consistent with Sweeney and Becker, who surveyed 85 port and maritime infrastructure engineers on the inclusion of sea-level rise projections in port infrastructure design (Sweeney and Becker, 2020). They found that while sea-level rise is often included in the design of protective structures (e.g. breakwaters, seawalls), it is less often in the design of berthing structures and very rarely in the design of connectivity or cargo storage structures. More specifically, several barriers identified to include sea-level rise in design are a lack of engineering standards or guidelines, project funding, and the difficulty to incorporate sea-level rise in the retrofit or upgrade of existing infrastructure. More generally, the lack of forward-looking approaches to climate change adaptation can be attributed to the limited availability of downscaled projections of climate extremes. While around half the ports have downscaled projections of changes in sea-level rise, for other climate extremes (e.g. precipitation, temperature, wind, waves, extreme water levels) this less common (between 23% and 35%) (UNCTAD, 2017a) (see Figure 2.8). However, even if downscaled projections are available, they are often on medium-long time frames only. In fact, of those having downscaled projections, the majority of ports only have projections for 10 years, except for sea-level rise where the majority of ports have projections of over 50 years.

Finally, surprisingly little is known about the types of adaptation options that ports consider to implement. Only Yang *et al.* surveyed 14 major Chinese container ports on adaptation preferences and the perceived costs and benefits of these options (Yang *et al.*, 2018). Interestingly, it showed that improving the resilience of transport infrastructure and utilities in the port area to storm surge flooding is perceived to be the most cost-effective option. Other cost-effective options identified are diversifying land connections to the port to avoid overland access issues associated with sea-level rise, and moving flood-prone facilities away from existing locations.

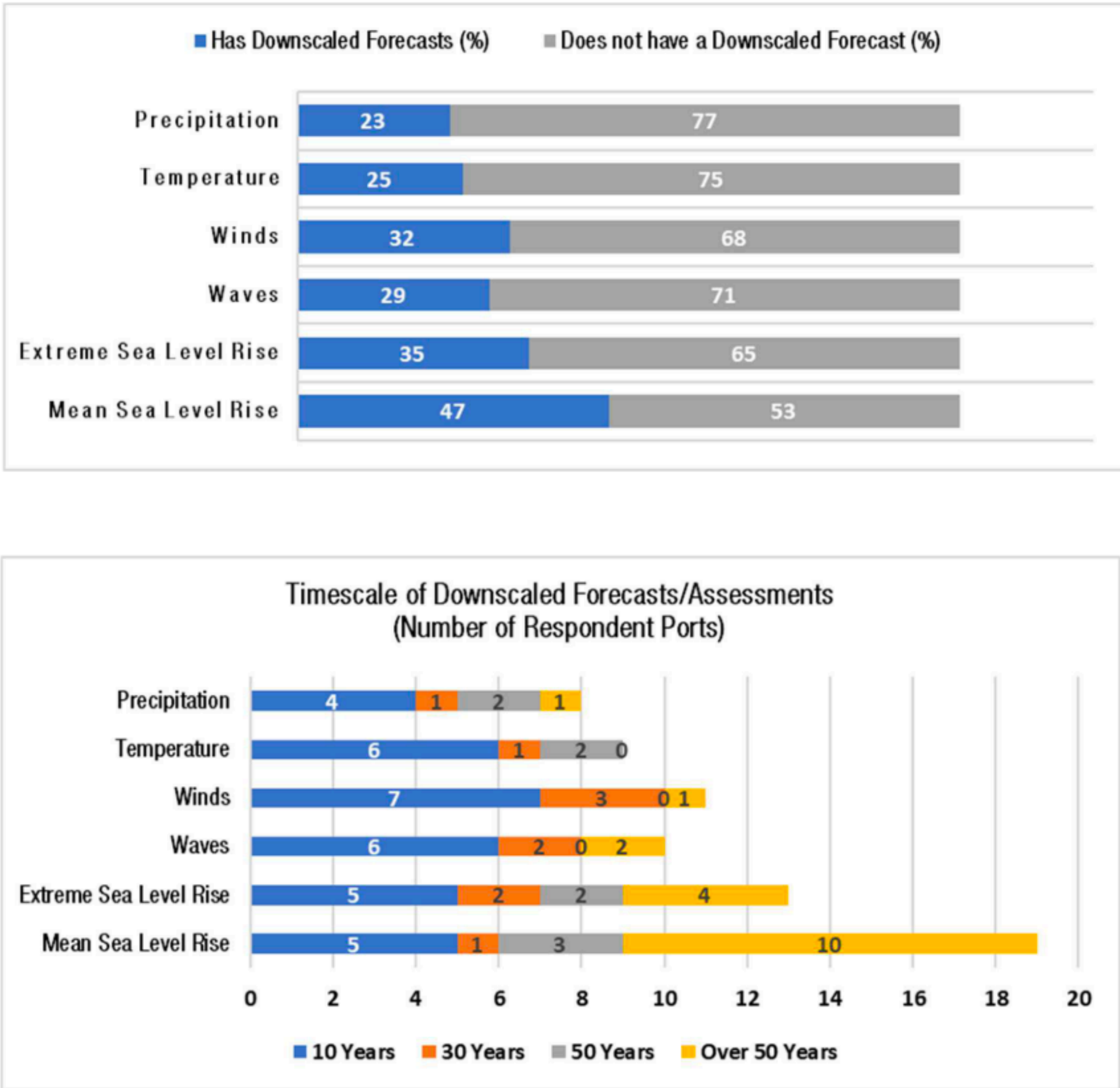

Figure 2.8: Response of port authorities when asked about the availability of downscaled forecasts of climate variables (top panel) and the timescale of downscaled forecasts if available (bottom panel) (UNCTAD, 2017a).

2.6.2 Adaptive capacity of ports

Alongside the existing adaptation practises, several surveys and studies have tried to evaluate critical thresholds of port adaptation. For instance, the ports surveyed by UNCTAD reported that they would face significant difficulties with two metres of sea-level rise, while half the ports mentioned that they could cope with sea-level rise of three metres or more (UNCTAD, 2017a). This corroborates earlier findings of Becker *et al.*, where most ports (58%) responded that a one to two metre sea-level rise threshold would cause a problem for adaptation, while 83% responded that sea-level rise of over two metre would cause major operational problems (Becker *et al.*, 2012). This is in line with expectations, as most port authorities (~60%) adopt a design standard of a historical 1-in-100 year event for expansion plans (e.g. new quays) (Becker *et al.*, 2012).

Other studies have tried to identify future adaptation limits of port facilities in technical terms. Esteban *et al.,* for instance, analysed the adaptation strategies taken by five ports in Indonesia and Japan that suffer some extreme subsidence, i.e. five – ten years of subsidence in these ports equals sea-level rise projections until the end of the century (Esteban *et al*., 2020). In some cases, technical limitations to raising port terminals were identified, for instance, because of the need for additional piling, while in other cases port authorities were confident that raising existing wharfs can be done relatively easy and cost-efficiently up to around two metre. The ports surveyed in this work are, however, relatively small ports with limited surface area to raise. In the survey of Sweeney and Becker, port engineers commented that retrofitting existing infrastructure, such as raising deck heights, is financially prohibitive, especially for large terminals (Sweeney and Becker, 2020). The technical difficulties of retrofitting infrastructure has also been noted as part of retrofits of old quay walls in Italian ports (e.g. Genoa, Ravenna, Naples, Messina, and Gaio Tauro), some of which were built in the 18th century. In particular, performing major upgrades (e.g. jet-grounding, concrete slab, new piling, ground anchoring) can be more expensive than building a new quay wall (ranging from 30,000 – 60,000 Euro per metre) (Ruggeri, Fruzzetti and Scarpelli, 2019).

2.6.3 Summary adaptation practices

The various industry surveys and modelling studies have underlined that most ports need to retrofit existing infrastructure, such as terminals, drainage, access roads and breakwaters as a result of a changing climate. Despite that fact that most ports will be able to cope with sea-level rise values that will likely not be exceeded by the end of the 21st century, many ports also face limits to adaptations. In particular, retrofitting existing port infrastructure to cope with changing environmental boundary conditions can become prohibitively expensive or technically challenging. Hence, it is still unclear to what extent retrofitting is financially feasibility in the long-term. On top of that, particular challenges and data gaps are identified, such as the lack of long-term climate change projections used for planning design, limited design guidelines, as well as a lack of clarity on how to deal with uncertainties and the timing of adaptation decisions. While some authors have argued for the need to embed flexibility in the design of adaptation infrastructure to cope with these uncertainties, such as adaptable breakwaters that can be gradually modified to cope with an change in the wave height and storm surges, the feasibility of this is hardly considered. Similarly, while different studies have underlined that incorporating adaptation upfront is likely to be much cheaper than having to retrofit later on, an analysis of the potential to do this is still lacking, in particular for new port expansions. This can largely be explained by the fact that most studies focus on the need to adapt existing infrastructure and little evidence is available on the need to adapt new port infrastructure that is required to cope with expected growth in maritime trade.

3 PORT DISRUPTIONS DUE TO NATURAL DISASTERS: INSIGHTS INTO PORT AND LOGISTICS RESILIENCE

Chapter 3 present empirical evidence of natural disasters affecting port operations. This information is used to provide insights in the average duration of hazard-induced port disruptions, as well as anecdotal evidence of the resilience of ports and the maritime system to cope with, and recovery from, such disruptions.

Paper: Verschuur, Koks and Hall (2020), Port disruptions due to natural disasters: Insights into port and logistics resilience, *Transportation Research Part D: Transport and Environment*, 85 (102393), doi:10.1016/j.trd.2020.102393

Contributions: Jasper Verschuur: Conceptualization, Methodology, Formal analysis, Writing – Original Draft, Writing – Review & Editing, Visualization. **Elco Koks**: Conceptualization, Writing – Review and Editing, Supervision. **Jim Hall**: Conceptualization, Writing – Review and Editing, Supervision

Data and code availability: The database of port disruptions is available from https://github.com/jasperverschuur/Port_Disruption_database. The AIS data for the United States and Australia is publicly available at the sources mentioned in the text.

Abstract: Ports are located in low-lying coastal and riverine areas making them prone to the physical impacts of natural disasters. The consequential disruptions can potentially propagate through supply chains, resulting in widespread economic losses. Previous studies that quantify the risks of port disruptions have adopted various modelling assumptions reflecting the resilience of individual ports and marine network logistics. However, limited empirical evidence is available to validate these modelling assumptions or to provide a deeper understanding of the ways in which operations are adapted during and after disruptions. Here, we use vessel tracking data to analyse past port disruptions due to natural disasters, evaluating 141 incidences of disruptions across 74 ports and 27 disasters. Results show a median disruption duration of six days with a 95th percentile of 22.2 days. All analysed events show multiple ports being affected simultaneously, challenging some of the studies that only focus on single port disruptions. Moreover, we find that the duration of the disruption scales with the severity of the event, with an increment of 1.0m storm surge or 10m/s wind speed associated with a two day increase in disruption duration. In contrast to commonplace assumptions in model studies, substitution between ports is rarely observed during short-term disruptions. On the other hand, production recapture happens in practice in many cases of port disruptions. In short, empirical vessel tracking data provides valuable insights for future modelling studies in order to better approximate the extent of the disruption and the potential resilience of the port and maritime network.

3.1 Introduction

Ports are critical nodes in the global trade network. Ports form the linkages between hinterlands and determine the location and distribution of global supply-chains (Notteboom and Rodrigue, 2008; Becker *et al.*, 2013; Ng *et al.*, 2015). They are strategically located close to coastlines and riverine areas to provide access to global maritime and inland water transport networks. However, their location makes them potentially vulnerable to natural disasters, such as coastal flooding (e.g. tropical cyclones, hurricanes), riverine flooding and earthquakes. A survey by the UNCTAD in 2017 (UNCTAD, 2017a) showed that 72% of the port authorities that responded have been impacted by climatic events, causing delays (60%), disrupting operations (76%) and physical damages (45%). Given a port's vital role in the global supply chains, port disruptions may induce shocks throughout the regional and global economy (Rose and Wei, 2013). Therefore, understanding past port disruptions and projecting future changes in port disruptions from natural disasters is vital for building resilience into the global port and trade network.

The impacts of natural disasters on transportation systems, including ports, can be multifaceted. A port disruption can first reduce the amount of freight a port can process for a certain duration, causing delays, the depreciation of goods and, in case cargo is re-routed, additional transportation costs (Omer *et al.*, 2012; Achurra-Gonzalez, Angeloudis, *et al.*, 2019). Cyclone Yasi, in 2011, closed the port of Brisbane for ten days, causing a total of AUD50 million in losses and decreasing the annual throughput with 6.4 percent (Cahoon *et al.*, 2016). In case of physical damages to ports, the functioning of ports may be severely impaired, with large costs involved to rebuild port assets and a long term disruption to the logistics network. Disruptions to vital transportation systems can further have large scale consequences for supply-chains that depend on these systems (Rose and Wei, 2013; Ng *et al.*, 2015; Lam, Liu and Gou, 2017). For instance, Hurricane Katrina in 2005 caused USD 1.7 billion damages to the Louisiana ports, resulting in an estimated USD 882 million losses of agricultural trade (Santella, Steinberg and Sengul, 2010; Trepte and Rice, 2014). Typhoon Maemi in 2003 left the Port of Busan inoperable for 91 days (Becker *et al.*, 2018), disrupting global maritime trade (Lam, Liu and Gou, 2017).

3.2 Literature review

Here, we will briefly discuss previous research that has focused on providing empirical evidence of past port disruptions (Section 2.1), potential economic consequences of port disruptions (Section 2.2), and the approaches to mitigate the negative consequences of port disruptions (Section 2.3).

3.2.1 Empirical evidence port disruptions

Several studies have looked at the past occurrence of port disruptions due to natural disasters. Trepte and Rice (2014) collected data on 28 incidences of port disruptions (caused by various hazards) between 2004 and 2010, showing that the median disruption duration equals three days with a standard deviation of six days. Lam and Su (2015) discussed 15 disruptions between 2001 and 2011 in Asia, including seven natural disasters, with closure durations ranging from 1 to 91 days. Adam *et al*. (2016) elaborated on maritime disruptions in the UK from 1950 to 2014, identifying 88 events of which 48% were caused by wind storms or storm surges. Interestingly, an increase in wind-induced port disruptions is reported, while disruptions associated with storm surges have decreased. Cao and Lam (2019) assess weather-induced port disruptions between 2013 and 2017 for the Port of Shenzhen, finding a total number of 170 weather events that caused downtime. The authors find that the month March has an average monthly downtime of seven days between 2013 and 2017, mainly associated with fog, whereas the months of July and August have an average monthly downtime of around four days due to typhoons and rain. In short, port disruptions largely vary according to the type of event, magnitude, continent and port, making it hard to generalise the results.

A small numbers of studies have explored the empirical analysis of port functioning during and after natural disasters using empirical vessel tracking data (Farhadi *et al.*, 2016; Touzinsky *et al.*, 2018). These studies have focused on the port of New York/New Jersey during Hurricane Sandy (2012) (Farhadi *et al.*, 2016) and the ports of Savannah, Charleston and Jacksonville during Hurricane Matthew (2016) (Touzinsky *et al.*, 2018). They showed how port disruptions follow a classical resilience curve consisting of the initial shock, a recovery phase and an adaptation phase (Linkov *et al.*, 2014; Grafton *et al.*, 2019). Still, differences can be observed between events and ports, which raises questions what the critical drivers of ports resilience are. This type of analysis has not yet been explored beyond the handful of ports in the United States, but provides a generic way to analyse port disruptions on a global scale.

3.2.2 Impact modelling port disruptions

Research focused on modelling the economic impacts of port disruptions use a variety of approaches, depending on the spatial scale of the impact analysis (e.g. port-level, regional-level, national-level). Port-level approaches either use hydrodynamic or extreme weather simulation models in combination with operational thresholds of ports (Zhang and Lam, 2015; Esteban, Takagi and Shibayama, 2016; Sierra *et al.*, 2017; Camus *et al.*, 2019), or a simulation model of the port functioning in order to estimate the economic losses of downtime for a port (Zhang and Lam, 2016; Cao and Lam, 2019). The abovementioned studies rely on a relationship between the event (e.g. wind speed, surge height, earthquake magnitude) and the resulting downtime, which is often hard to obtain from data. Ports often work under increased safety protocol before operational thresholds (e.g. wind thresholds for gantry cranes) are exceeded (Berle, Rice Jr. and Asbjørnslett, 2011; Omer *et al.*, 2012), which means that thresholds do not have to be exceeded before operations are disrupted. Apart from a curve that relates the port recovery to the severity of an earthquake in Japan (Akakura *et al.*, 2015), such general relationships do not yet exist for ports.

System-wide approaches model the freight assignment in case of port disruptions using freight modelling (Jones *et al.*, 2011) or empirical approaches (Paul and Maloni, 2010; Akakura *et al.*, 2015). Although they can predict the optimal diversion paths of freight, they are often static models and do not provide insights into the dynamic assignment, including port and liner constraints, over time. Other approaches use dynamic liner optimisation models (Novati *et al.*, 2015; Achurra-Gonzalez, Angeloudis, *et al.*, 2019) to model the vessel assignment over time and associated cost of vessel rerouting after node or link perturbations. A different strand of literature have quantified the economic consequences of port disruptions by assessing the inter-industry supply-chain interlinkages of goods transported through a specific port (Park *et al.*, 2008; Rose and Wei, 2013; Pant, Barker and Landers, 2015; Thekdi and Santos, 2016; Rose, Wei and Paul, 2018). Such evaluations use a combination of port disruption scenarios, a port simulation model, and a macroeconomic model to propagate the impacts of disruptions to the regional or national economy.

The abovementioned literature often rely on a scenario analysis of port disruptions, including the duration of the disruption and the occurrence of single versus multiple ports disruptions. Those focusing on disruptions from natural disasters or extreme weather have implemented durations in the order of 1 – 10 days (Jones *et al.*, 2011; Pant *et al.*, 2014; Zhang and Lam, 2015, 2016; Cao and Lam, 2019). Others have assumed longer closures such as 14 days (Paul and Maloni, 2010; Pant, Barker and Landers, 2015), 30 days (Thekdi and Santos, 2016) or two months (Achurra-Gonzalez, Novati, *et al.*, 2019), with the latter focusing on a specific earthquake event. However, given the variety of scenarios, and the potentially sensitivity of the results to this, it is important to understand how these scenarios relate to past port disruptions in terms of severity. For instance, little substantiation is provided what the recurrence interval of these scenarios are (e.g. 10 day disruptions occurs once every x years). Moreover, most of the aforementioned studies only consider single port disruptions (Park *et al.*, 2008; Rose and Wei, 2013; Pant, Barker and Landers, 2015; Thekdi and Santos, 2016; Zhang and Lam, 2016; Rose, Wei and Paul, 2018; Camus *et al.*, 2019; Cao and Lam, 2019). However, a single versus multiple port disruption scenario might affect the results in terms of losses and system response. For instance, Paul and Maloni (2010) showed that a multiple port versus a single port disruption scenario (14 days) increases the resulting losses by a factor 4.6.

3.2.3 Mitigation strategies port disruptions

The most prominent strategies to minimise the negative consequences of port disruptions from a logistics point of view are production recapture (i.e. ports can make up for disruption by handling more cargo once they become operational again) and port substitution (i.e. part of cargo can be diverted to other port/ports). Most modelling studies assume that port substitution readily happens, either by modelling the alternative assignment options explicitly (Paul and Maloni, 2010; Jones *et al.*, 2011; Novati *et al.*, 2015; Achurra-Gonzalez, Angeloudis, *et al.*, 2019) or by including it as a resilience option in an impact analysis using macroeconomic models (Rose and Wei, 2013; Rose, Wei and Paul, 2018). However, port substitution might not occur in practise, due to a variety of factors: the earlier mentioned simultaneous port disruptions, draught constraints, hinterland connections, specialised equipment, and contractual restrictions (Trepte and Rice, 2014; Akakura *et al.*, 2015; Hamano and Vermeulen, 2019). The ongoing trends in port development are on the one hand an increasing specialisation of smaller ports and on the other hand a rise in large gateway ports, driven by the ever-increasing size of vessels that can only call at a limited set of ports (Notteboom and Rodrigue, 2008; Ducruet, Itoh and Joly, 2015). Trepte and Rice (2014) pointed out that due to this trend, a disruption in a large port/set of ports in the U.S.A. will inevitably lead to losses to the economy given an insufficient capacity in substitution ports. On top of that, ports are becoming more horizontally embedded within maritime supply-chains (Notteboom, 2006; Notteboom and Rodrigue, 2008; Rodrigue and Notteboom, 2009; Wendler-Bosco and Nicholson, 2019) with carriers owning stevedoring companies and hinterland connections, or carriers having long-term contracts with specific ports for cargo handling. This all makes the occurrence of port substitution limited, with carriers often choosing to either wait or implement strategies such as port swapping or port skipping (Li, Qi and Lee, 2015).

Recent empirical work (Sytsma, 2017; Friedt, 2018) analysed changing port-level trade flows during and after a number of hurricanes in the U.S.A. and found limited evidence of port substitution. Hamano and Vermeulen (2019), however, found evidence that in Japan about 40% of the export was substituted to other ports in the months after the Great

East Japan Earthquake in 2011. However, this could be driven by the type of commodities Japan exports (e.g. car manufacturing) that generally have little inventories (and therefore a larger export push), the two month disruption of multiple ports, and because of the country's spatial configuration, which makes it relatively cost-efficient to switch from ports on one side of the country to the other (Akakura *et al.*, 2015; Hamano and Vermeulen, 2019). The extent to which port substitution can occur does steer the resulting losses. For instance, Achurra-Gonzalez *et al.* showed that disruption losses have an order of magnitude difference depending on the assumption of diversion rate incorporated (they apply cases 0 – 100% diversion). Therefore, diversion rates, such as the 90% diversion rate used by Rose and Wei (2013) and Rose, Wei and Paul (2018) as a potential resilience strategy, should be empirically tested for its viability.

Instead of diverting cargo to alternative ports, ports can recapture the delayed cargo that has not been cancelled (via port skipping or swapping) by increasing their productivity after the port has become operational again (Akakura *et al.*, 2015). The ability of a port to do this depends on the level of utilisation of the port and the ability to temporarily increase throughput (level of storage, number of tugs and pilots, number of trucks and trains available to transport). Ports with a high utilisation rate and already large congestion problems will face difficulties in recapturing cargo, whereas ports with lower utilisation rates (Fan, Wilson and Dahl, 2012) will more likely recapture their cargo. In case of ports transporting goods with a seasonal character (e.g. harvesting season agriculture), the ability to recapture also depends on the timing of the disaster. However, this strategy is often not included in modelling approaches.

The occurrence of port substitution and production recapture in reality is mixed, making it hard to understand the current level of resilience already in the system and evaluate the viability and benefits of various strategies to improve port and supply-chain resilience.

3.3 Research gap and objectives

As pointed out in the literature review, little empirical evidence is available on port disruptions in real-world situations. Providing an empirical database of past port disruptions can improve our understanding on the occurrence and severity of disruptions across different geographical scales. Using this data to derive a relationship between the severity of the event and the resulting downtime could support risk management purpose of ports. Furthermore, empirical data can support model-based studies by creating more realistic scenarios of port disruptions, in terms of duration and spatial extent (e.g. single versus multiple ports), and help refine some of the modelling assumptions made on the recovery and response of the logistic network. Finally, analysing the dynamics of port disruptions over time can provide useful insights in the resilience of supply-chains and can be used as a tool to evaluate how different strategies implemented by ports are enhancing the recovery after disruptions.

In this paper, we build upon previous analysis (Farhadi *et al.*, 2016; Touzinsky *et al.*, 2018) and use Automatic Identification System (AIS) data to provide empirical evidence of vessel movements in and around ports (both affected and non-affected ones) during and after disruptions. We use this data to fill in some of the research gaps by evaluating the disruption duration and the resilience of ports, and deriving a fragility curve for U.S.A. ports. In addition, we evaluate the port and logistic-level resilience by looking into the mitigation strategies implemented, either via ports trying to (partially) recapture goods or carriers seeking alternative, non-affected, ports to take over some of the goods destined for a disrupted port.

In total, we analyse 141 incidences of port disruptions due to natural disasters. Although we are constrained by data availability (U.S.A. 2011-2017, Australia 2012-2019 and globally April 2019 – December 2019), some valuable insights can be provided by the events analysed, including a number of implications for port authorities and future research efforts. We start by providing an overview of the data sources used and analytical approach adopted (Section 3.4). This is followed by a systematic analysis of the events, including duration of the disruptions and resilience of ports (Section 3.5.1). Next, evaluate the relationship between the magnitude of the event and the duration of the disruption for U.S.A. ports (Section 3.5.2) and the occurrence of multiple versus single port disruptions (Section 3.5.3). Moreover, we look at the recovery and adaptation approaches of ports and how real-world observations compare to assumptions made in simulation-based approaches (Section 3.5.4 and 3.5.5). We end with the implications of our work and provide a set of recommendations for further studies on port disruptions (Section 3.6), followed by a conclusion (Section 3.7).

3.4 Data and methods

3.4.1 AIS data and coastal surge and wind speed data

AIS was introduced by the International Maritime Organisation (IMO) to improve safety at sea and provides detailed data on the location, speed and direction for all vessels with an AIS transponder (>300 GT vessels need a mandatory AIS receiver), that send information to terrestrial or satellite receivers, every few seconds to minutes. AIS data has successfully been used to inform fisheries monitoring, maritime emissions, spatial planning and trade estimation (De Souza *et al.*, 2016; Adland, Jia and Strandenes, 2017; Fournier *et al.*, 2018; Metcalfe *et al.*, 2018; Liu *et al.*, 2019). Although the coverage of vessels has increased tremendously over the years, some challenges related to the reception of lower powered AIS transponders, the revisit time of satellites and general accuracy of the data still persists (Fournier *et al.*, 2018).

For this study, AIS data is collected from various sources. Monthly AIS data for the U.S.A. is downloaded from the AIS database of MarineCadastre (MarineCadastre, 2019) that covers data collected by the U.S. Coast Guard. This includes raw data from 2009-2017 per UTM zone. For Australia, monthly AIS data can be downloaded from the data service of the Australian Maritime Safety Authority (Australian Maritime Safety Authority, 2019) for the whole country over the period 2012-2019. Only data points with a minimum time interval between successive vessel position reports of 60 minutes are included in this dataset. For the globally covering data from 01-04-2019 till 01-12-2019, data was retrieved via a partnership with the UN Global Platform AIS Task Team initiative, which aims to develop algorithms and methodologies to make AIS data useful for a variety of fields and applications (traffic, economic trade, fisheries, CO2 emissions). Within the time period of available data, we search for natural disasters that have occurred in the vicinity of ports from different sources (EM-DAT database, NOAA Hurricane Centre, Australian Bureau of Meteorology and news articles). We focus particularly on hurricanes (here used interchangeably with tropical cyclones and typhoons), that are associated with extreme wind, waves and surges, and riverine flooding, that can disrupt port and hinterland infrastructure. This set of disasters and associated ports forms our initial set of port-event combinations to evaluate. Other natural disasters like heatwaves, precipitation and fog can affect port operations, but are often of short duration (order of few hours) (Cao and Lam, 2019) and hence hard to detect using the daily aggregation we adopt.

For the U.S.A. ports under consideration (N = 54), we also collected the peak surge and wind speed of the hurricane events to relate the extent of the disruption to the magnitude of the event. The peak surge and wind speed are collected from the National Oceanic and Atmospheric Administration (NOAA, 2020) with values taken from the closest gauge station that has data during the particular events. This may induce some bias as tide gauge/wind stations and have different distances to the ports of interest.

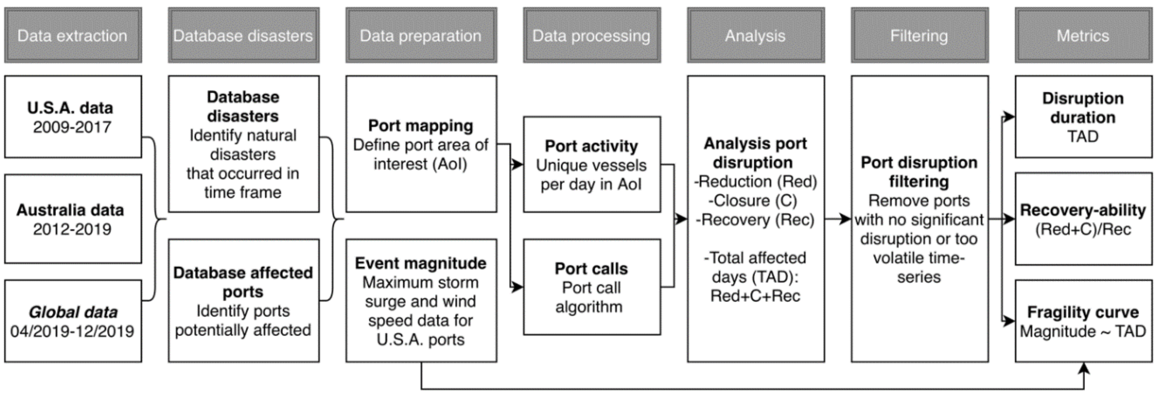

Figure 3.1: Workflow of the analytical approach taken in this paper.

3.4.2 Analytical approach

An overview of the workflow is included in Figure 3.1. For every port under consideration, we derive a port activity time series by counting the number of unique vessels over time within a specifically defined port area using the AIS data. Moreover, we derive the vessel calls per port by looking at the ingoing and outgoing movements of vessels in our area of interest. As in Touzinsky *et al*. (2018), the total area of interest includes the port area and navigation channel(s). For some port clusters (multiple ports within same bay), we take strategic positions to count vessels (e.g. entrance Tokyo Bay, entrance Galveston Bay) to capture multiple ports boundaries at once. We solely extract cargo (container, general cargo, dry bulk etc.) and tanker (oil, chemical, refined oil and chemical products etc.) vessels to focus on goods-carrying vessels and retrieve data over a period of three months for each event (the month before, during and after the event), thereby excluding other purpose vessels in the port area (e.g. tugs, piloting vessels, bunkering vessels, passenger ships, fishing boats and private yachts). For the remainder, we use port activity as our main metric, as it better resembles a port's operational status, but results are consistent if port calls have been used instead.

We filter out the incidences of port disruption where the vessel count reduction is less than 20% of normal operations and cases where it is hard to distinguish if a reduction is caused by the disaster or the natural variability in vessel activity (e.g. port Hampton Roads and port New York-New Jersey during 2017 Hurricane Maria). We have therefore also excluded smaller, less busy ports from the analysis (e.g. port Morehead City in U.S.A. and port Bunbury in Australia), as it is hard to distinguish the disruption from a time series that includes periods of inactivity. However, large gateways ports handle the majority of goods (Ducruet, Koster and van der Beek, 2010) and are therefore most significant from a trade perspective. In the end, our database consists of 141 incidences of disruptions across 74 ports (12 countries) during 27 events (9 hurricanes, 2 floods, 12 tropical cyclones and 4 typhoons) where port operations have been affected. These disruptions range from minor operational change (~20-50% reduction port activity) up to total shutdown of port operations for multiple days. Some examples of port disruptions are provided in Figure 3.2, including Hurricane Harvey (2017) affecting the ports of Houston-

Galveston-Freeport (Figure 3.2a), Tropical Cyclone Veronica (2019) impacting Port Dampier (Figure 3.2b), Hurricane Sandy (2013) affecting the port of New York-New Jersey (Figure 3.2c), and Port Haimen during and after Typhoon Lekima (2019) (Figure 3.2d). For each incidence, we count the number of days that the port activity is in a state of Reduction (Red), Closure (if closed) (C) and Recovery (Rec) till pre-disaster level. Resilience is commonly defined as the ability to resist and recover from, and adapt to, adverse events (Linkov *et al.*, 2014). It is hard to design an overarching resilience metric, because definitions of resilience differ in the academic literature, including which factors contribute to resilience and how these factors can be measured, maintained and enhanced (Klein, Nicholls and Thomalla, 2003; Grafton *et al.*, 2019). We therefore focus on two metrics that are subcomponents of resilience. First, we use the total number of affected days (TAD) as a metric to approximate the extent of the disruption, which is equal to the summation of Red, C and Rec. Second, we approximate the recovery-ability of ports by dividing the number of days a port activity is reduced and halted (closed) by the number of days its takes to recover (disruption/recovery ratio). In some cases, ports adapt to a new operational state after a disruption, either related to a lower pre-disaster state (part of the port or hinterland inoperable for a long period of time) or a higher post-disaster state (increasing the productivity of the operations).

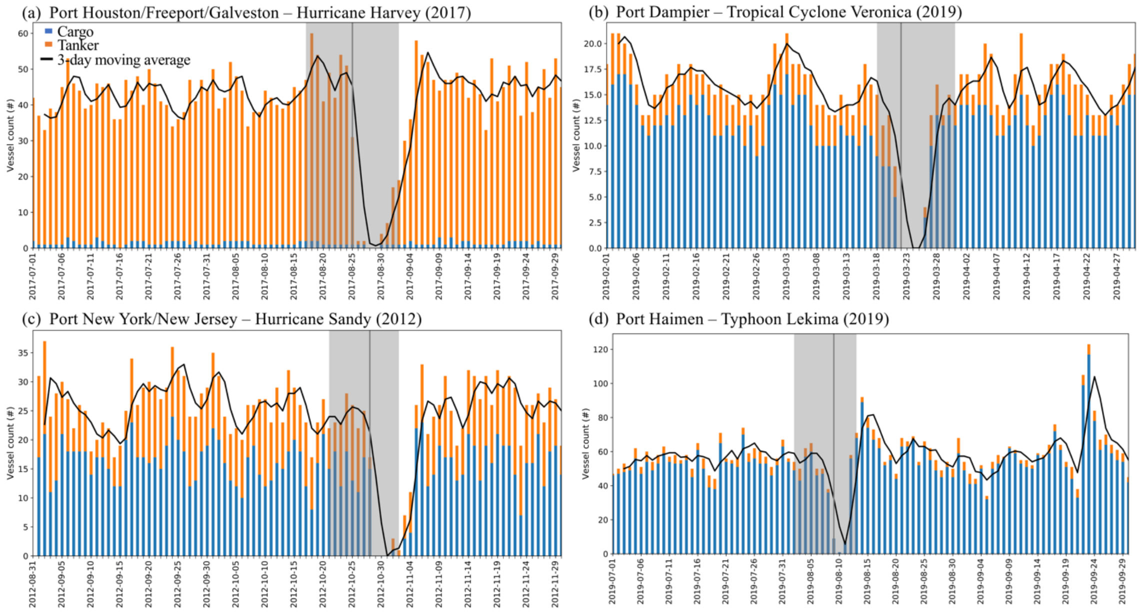

Figure 3.2: Overview of port disruptions for four ports and events: (a) Port of Houston/Freeport/Galveston (U.S.A.) during Hurricane Harvey, (b) Port Dampier (Australia) during Tropical Cyclone Veronica, (c) Port New York/New Jersey (U.S.A.) during Hurricane Sandy, and (d) Port Shanghai (China) during Typhoon Lekima. The grey shade represents the formation and dissipation of the event, whereas the grey line indicates the date of making landfall.

3.4.3 Analysis

We use the abovementioned data to do a number of analysis. First, we analyse the distribution of the TAD for both ports that are closed and not closed. We do a similar exercise for the distribution of the recovery-ability of ports. Second, for U.S.A. ports and events, we derive a relationship between the severity of the events (in terms of wind speed and surge height) and the TAD by analysing the correlation coefficient and by fitting a linear regression. Third, we study the likelihood of a simultaneous disruption at multiple ports. Fourth, we provide evidence for the occurrence of port substitution and production recapture using the time series of port activity.

3.5 Results

3.5.1 Duration disruptions and recovery

Figure 3.3a shows the normalised histogram together with the distribution (solid line) of the TAD for the events. Of the 141 disruptions we investigated, 69 ports show a completely shut down, whereas the remaining 72 ports were only partially affected (ranging from only 20% affected to limited operations). The median TAD equals six days for the ports that have been closed with an 5-95 quantile of 4 – 22.2 days (red histogram Figure 3.3a). For the ports that did not completely close, the median TAD is 5 days with a 5-95 quantile of 2 – 11 days (green histogram Figure 3.3a). The distribution is highly skewed with the upper quantile values being influenced by some extreme cases like the 2011 Mississippi flood, which, according to our data, closed the Port of Baton Rouge for 11 days and part of the inland water transport network, affecting transport at the Port of Rouge for 33 days and the Port of South Louisiana for 30 days (although not closed). Two other extreme cases are the 2019 Typhoon Lekima that caused flooding and landslides in the port city of Wenzhou, causing the port and inland water network to become inoperable for 45 days, and a 45-day disruption at the Port of Hay Point after the 2017 Tropical Cyclone Debbie. The latter was caused by flooding of the major railways connecting the port with the main port supplying coal mines (ABC News, 2017). These examples show that hinterland disruptions can affect port operations significantly, in particular export-orientated ports that handle low-value bulky goods (like ores and cereals) that disproportionally rely on their hinterland infrastructure. Some of the most extreme disruptions in the database are Hurricane Dorian affecting operations at the Port of Freeport (21 days TAD), 2017 Hurricane Harvey affected the ports of Port Arthur and Beaumont (18 TAD), Port of Corpus Christi (14 TAD) and Houston (11 TAD), and 2019

Tropical Cyclone Veronica closing Port Walcott (16 TAD). These ports have important functions within the global supply-chain, such as Freeport's function as transhipment hub for U.S.A. ports, Port Walcott's role as one of the main iron ore exporting ports for the Chinese and Japanese industry (Beresford, Pettit and Liu, 2011) and the central role of the Gulf of Mexico ports in the international trade of refined oil products (Santella, Steinberg and Sengul, 2010).

The distribution of the recoverability metric for both closed and non-closed ports is shown in Figure 3.3b, which larger values indicating enhanced recoverability. The median recoverability is close to 2.0, indicating that the number of days it takes to recover is on average half the time of the original disruption by reduction or closure. However, especially for ports that are closed the spread is large and multimodal. For instance, during Hurricane Harvey (2017), the port of Corpus Christi was disrupted ten days and took four days to recover, whereas the port of Lavaca was also disrupted ten days (and closed two days longer), but recovered in only two days. A similar observation can be made for the ports of Port Hedland and Port Dampier after Tropical Cyclone Veronica (2019). The former was disrupted five days and took five days to recover, whereas the latter was disrupted eight days and took three days to recover. Port Walcott, also disrupted by TC Veronica (2019), needed seven days of recovery after being disrupted for nine days (seven days closed). Port Walcott, compared to the other two ports, has no breakwater or natural shelters and hence more vulnerable for the impacts of tropical cyclones.

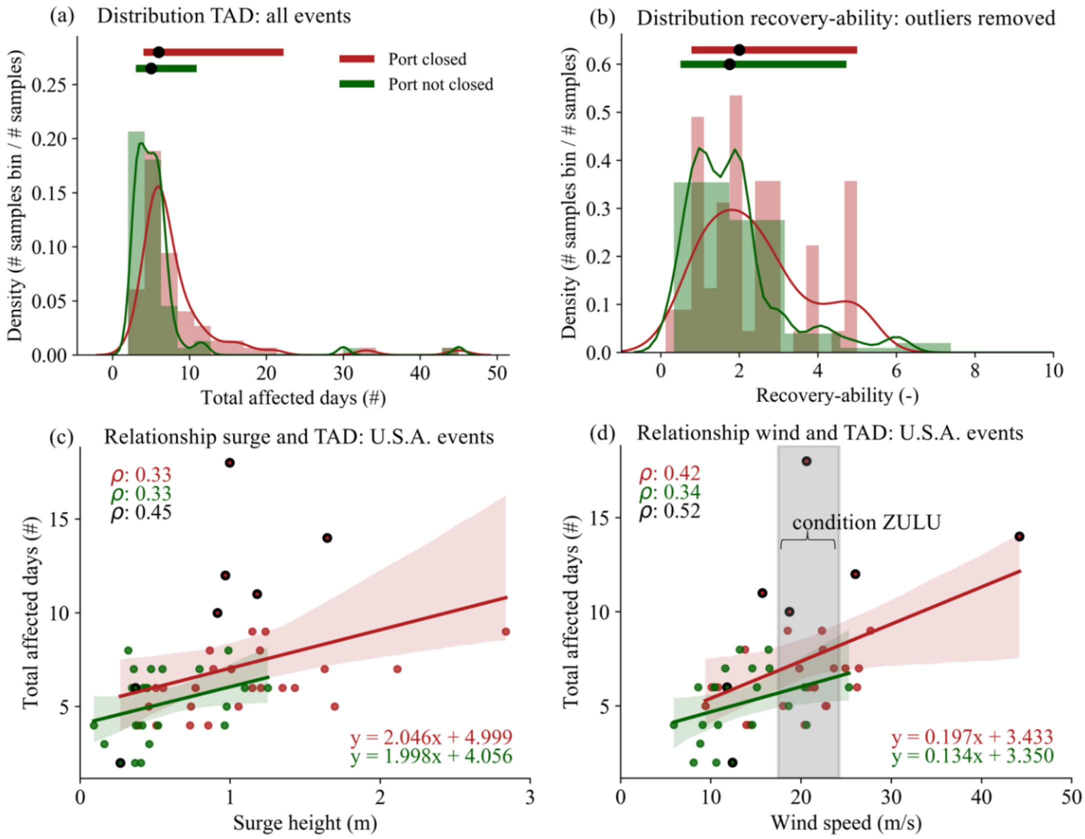

Figure 3.3: a) The distribution of the total affected days across all events where ports have been closed (red) or partly affected (green) with the median (black marker) and 5-95th percentile values depicted by the bar, (b) same as (a) but for the recovery-ability of the events, (c) The relationship between the peak surge height and the total number of affected days for all events and ports considered in the U.S.A. for ports. (d) The relationship between the peak wind speed and the total number of affected days for all events and ports considered in the U.S.A. The grey area depicts condition ZULU corresponding to gale winds that require a port to stop operations. The markers with a black edgecolor are associated with Hurricane Harvey.

3.5.2 Relationship between the magnitude event and total number of affected days

For the U.S.A. ports, we investigate the relationship between the magnitude of the event and the TAD. Curves that relate the magnitude of the event to the severity of the consequences are referred to as fragility curves in the disaster risk community (Meyer *et al.*, 2013). Fragility curves are valuable sources of information for various stakeholders, such as port authorities and logistics companies, as they can be used to identify critical thresholds (e.g. risk of getting delays more than x number of days) per port, and how the likelihood of such threshold may change in the future due to climate change.

Results are shown in Figure 3.3c-d for peak storm surge versus TAD and peak wind speed versus TAD. A linear trend can be observed with the magnitude of the event and the TAD, with an overall correlation of 0.45 for surge and TAD and 0.52 for wind speed and TAD. As expected, the largest surge and wind speed events are associated with port closures and longer TAD. This is related to the 'Hurricane Port Conditions' safety protocol in place in the U.S.A., which states that all waterfront operations should be suspended when condition ZULU is reached. Condition ZULU corresponds to sustained gale force winds (~17.5 – 24.2 m/s) that are predicted 12h before the hurricane makes landfall (see grey area Figure 3.3d). Correlations are smaller for the separated data, with a correlation of 0.33 (0.33) for surge and TAD for closed ports (non-closed ports) and 0.42 (0.34) for wind speed and TAD for closed ports (non-closed ports). Ports affected by Hurricane Harvey (indicated with black markers) are some extreme cases here given that the magnitude of surge and wind speed was moderately high, but the number of TAD very high. Hurricane Harvey was a slow-moving hurricane that reversed direction when moving over Texas (Kossin, 2018), affecting the area for a long duration and causing long-lasting limitations to operations. This example shows the importance of the event's duration for the inoperability, with recent projections showing an increase of the number of slow-moving hurricanes in the future associated with anthropogenic climate change (G. Zhang *et al.*, 2020). By fitting a linear regression through the data points (see graph for fitted line), the observation can be made that an additional 1m increase in storm surge is associated with 2.05 (2.00) increase in TAD for ports that are being shut (not shut). For wind speed, a 10m/s increment in wind speed results in a 1.97 (1.34) increase in the number of TAD for ports that are being shut (not shut).

3.5.3 Simultaneous port disruptions

Disasters like hurricanes can affect large areas simultaneously, either because multiple ports experience extreme conditions within their terminal areas or due to extreme conditions at sea that delay multiple vessels within a region. Figure 3.4 shows the TAD and the amount of days that ports are fully closed per event. Single port disruptions rarely happen and all events have multiple ports being simultaneously affected to some extent. Of these events, 15 out of 27 have simultaneous full port closures, showing that full port closures can be more localised. Given that the simultaneously affected ports are usually closely located to each other, simultaneous closures will affect the possibility of diverting goods in a cost-efficient way (that is without significant rerouting costs). Therefore, freight assignment models that model single port disruptions may be overly optimistic about the spare capacity in potential substitution ports during events like hurricanes, whereas with more localised disasters (e.g. river flooding, landslides) this is a more realistic modelling assumption.

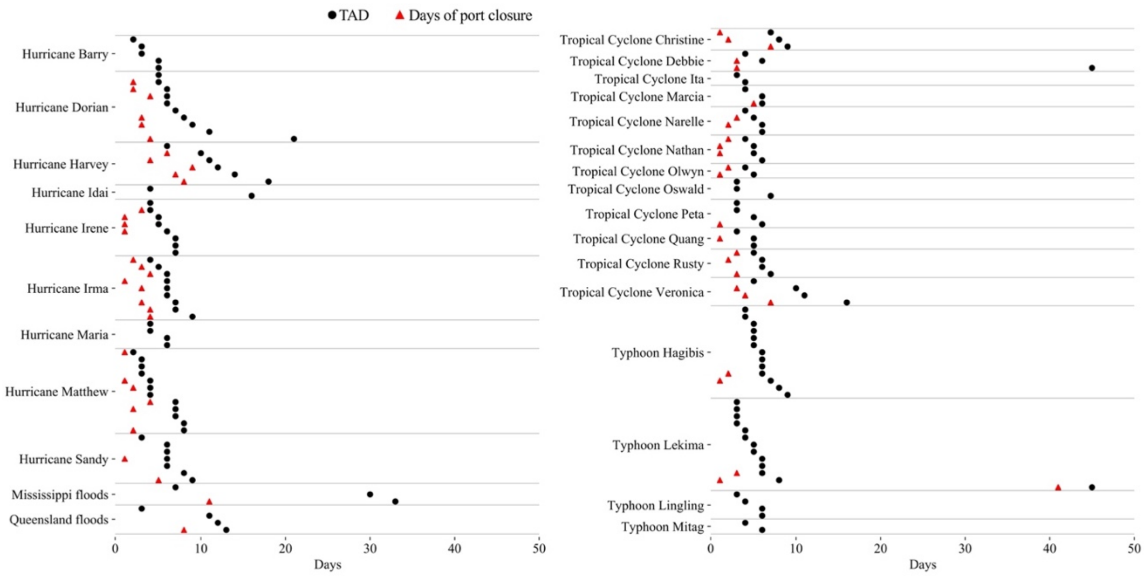

Figure 3.4: Overview of number of days affected and number of days closed per port and per event.

3.5.4 Port substitution

In our sample of ports, we have identified the closest (unaffected) ports for potential substitution options and analyse the time series to assess if there are clear signs of increased vessel activity at these ports. In contrast to the dominance of port substitution as a mitigation mechanism in model-based studies, we find very limited evidence of substitution occurring. Two incidences stand out as exceptions: the 2019 Hurricane Barry that caused a temporally spike in cargo vessel calls at the port of Fourchon (U.S.A.) (Figure 3.5a-b) and reported evidence of coal export substitution from the port of Abbot Point towards the neighbouring Hay Point, Dalrymple and Gladstone ports during the 2019 Queensland floods (Financial Review, 2019). The latter is hard to observe in the data for port Hay Point and port Gladstone given an overall reduction in vessel activity. Port Dalrymple (Figure 3.5c), however, received some extra vessels at the same time

Abbot Point (Figure 3.5d) experienced a decrease, but the limited number of vessels makes it hard to make well-backed statements about this.

The lack of port substitution could, however, be explained by the fact that our sample of disruptions is simply too short in duration to observe structural port substitution. For instance, after the 1995 earthquake that disrupted the port of Kobe, cargo flows were diverted to the ports of Osaka, Nagoya and Yokohama while transhipment flows were diverted to Busan (South-Korea) and Kaohsiung (Taiwan), some of which never returning back after the port got operational again two years later (Chang, 2000). Within our dataset, the port of Wenzhou, which was affected 45 days, has never reached its pre-disaster level of daily vessel activity again (around 50%), even three months after it became operational again. An analysis of the vessels that usually called at the port but never again after becoming operational again show that some of the vessels have diverted their port calls to the ports of Ningbo, Zhoushan and Shanghai, which agrees with previous work (Li and Oh, 2010) that identified these ports are competitors of one another.

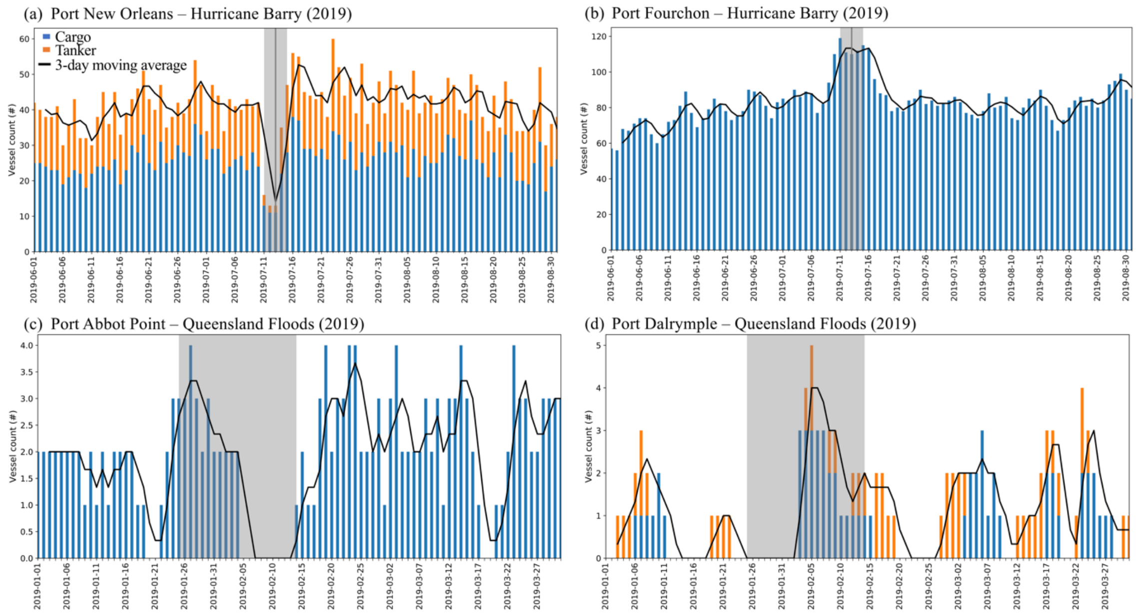

Figure 3.5: Port substitution from the Port of Abbot Point (a) towards Port Dalrymple (b) during the 2019 Queensland Floods that disrupted the railway between the coal mines and the Port of Abbot Point. The grey shade represent the formation and dissipation of the event, whereas the grey line indicates the date of making landfall.

3.5.5 Production recapture

We use to time series to assess to what extent ports increased their productivity after the recovery from an event and thereby recaptured part of their cargo lost during downtime. Figure 3.6 shows four ports with visible evidence of production recapture after a port disruption. For the Port of Baltimore (Figure 3.6a) after Hurricane Sandy, the Port of Jacksonville in the aftermath of Hurricane Irma (Figure 3.6b) and the Port of Savannah after Hurricane Matthew (Figure 3.6c), the productivity reaches its highest point within the three month time frame a few days after becoming operational again. These three ports show clear signs of the ability to temporality ramp productivity or increase capacity after short-term disruptions. For the port of Freeport after Hurricane Dorian (Figure 3.6d), a longer and more sustained recovery has taken place with production recapture spread out over the time frame between the end of September and early October. Freeport, an important transhipment hub in the Caribbean, most likely works closer to maximum capacity to maintain is position in the competitive transhipment industry (Notteboom, Parola and Satta, 2019), thereby taken longer to recapture their cargo flows. Whether or not production recapture is a feasible option and within what time range depends very much on the duration of the disruption, the type of cargo, and the characteristics of the port with respect to its ability to ramp up production.

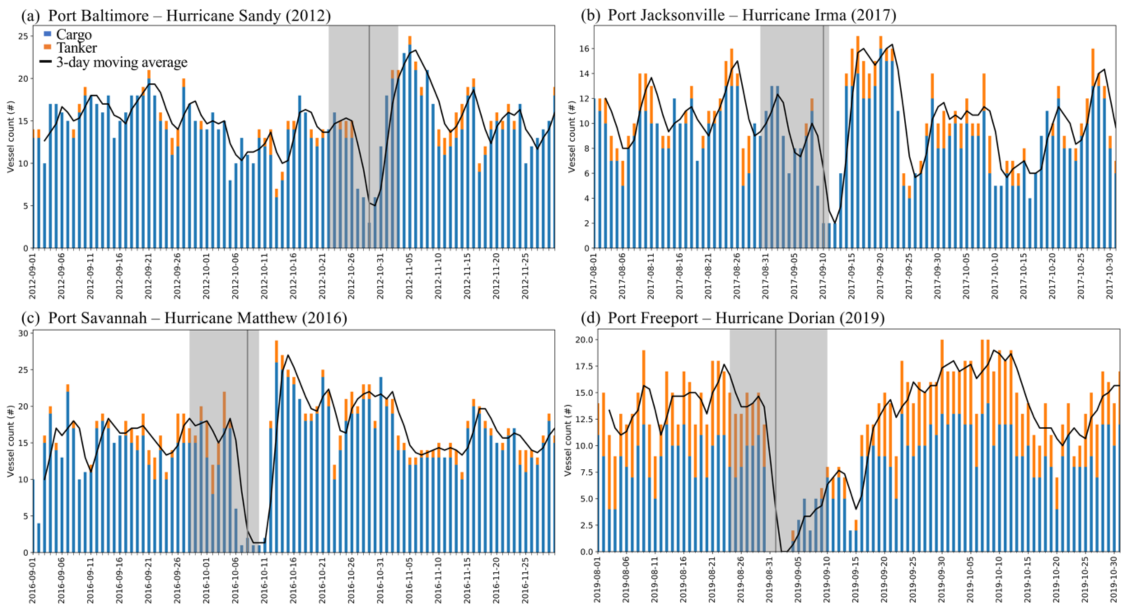

Figure 3.6: Evidence of production recapture after a port disruption: (a) Port Baltimore (U.S.A.) during Hurricane Sandy, (b) Port Jacksonville (U.S.A.) during Hurricane Irma, (c) Port Savannah during Hurricane Matthew (2016) and (d) Port Freeport (Bahamas) during Hurricane Dorian. The grey shade represent the formation and dissipation of the event, whereas the grey line indicates the date of making landfall.

3.6 Discussion

The disruption scenarios used in previous modelling work, which ranged from a few days up to 1-2 months, all fall within the distribution of port disruptions in our database. Moreover our findings of port disruptions fit well with other empirical reporting on the duration of disruptions (Trepte and Rice, 2014; Lam and Su, 2015; Adam *et al.*, 2016a;

Cao and Lam, 2019a). Short-term disruptions (order of few days) can be interpreted as events that caused a port to close or to work under reduced operability without causing devastating structural damages to the port. Closures in the order of 30 days or more can be considered associated with events where natural disasters have damaged the port or hinterland infrastructure, and prevents the port from fully operating until the damage has been repaired. This data can be used to create more realistic scenarios of downtime, including a first indication of the likelihood of observing a certain disruption severity. Moreover, the downtime related to natural disasters can be compared to the downtime due to other unforeseen events, such as electricity failure or oil spill, to improve risk management plans for port authorities. Alternatively, one can use the AIS data to assess how certain resilience indicators of ports have changed over time, and whether this can be attributed to certain measures taken (e.g. construction breakwater, increased safety protocol).

As mentioned, few studies have particularly focused on, and tested various configurations of, multiple port disruptions happening at the same time. We have showed that single port disruption due to hurricanes rarely occur, which has important implications for the potential losses (e.g. rerouting, physical damages, economic losses) and possible mitigation strategies (e.g. cargo diversion). Therefore, modelling studies that focus on a regional to national scale should consider creating scenarios of synchronous port disruptions to test the system, in particular when certain port clusters are affected (e.g. Gulf of Mexico ports in U.S.A. for export of refineries or Australian iron ore exporting ports). Predicting the occurrence of synchronous port disruptions, using for instance joint probability functions, is also relevant for business contingency plans and national-level policies to effectively respond to and accelerate the restoration of the logistic network after such an event.

From the fragility curve, a relationship (although weak) was found between the severity of the event and the duration of the disruption. Such scaling relationship can be used by port authorities to assess how changing conditions due to anthropogenic climate change will change the probability of occurrence of certain downtime periods. Moreover, it can be used to understand what type of events create the largest downtime. For instance, port disruptions associated with Hurricane Harvey were considerably longer given the severity of the event due to the slow movement of the hurricane. Hence, the relationship as observed today may shift in case these type of hurricanes are becoming more likely in the future, as predicted (G. Zhang *et al.*, 2020), with resulting negative consequences for port operations and supply-chains.

In terms of port substitution options, modelling assumptions on the diversion rate should be carefully chosen to comply with reality and not be too optimistic. Values such as the 90% diversion rate, as chosen by Rose and Wei (2013), seem high but can be justified by the specific type of port under consideration (Port Arthur and Beaumont) that have large ports such as Houston, New Orleans and Louisiana in their direct vicinity that can take over most of the tanker vessels calling at the Port Arthur and Beaumont. In general, a distinction should be made between short-term disruptions where port substitution is less likely and longer-term disruptions where cargo is structurally diverted to competitive ports in the area. Sensitivity testing of port diversion rates, as done in Achurra-Gonzalez *et al*. (2019a), is a recommended approach.

More generally, we have shown how AIS data can be used as an open-source tool to monitor port disruptions over time. This open up ways to evaluate the resilience of supply-chains, for instance, by seeing how port activity changes in trade-dependent ports or countries, whether ports with different network positions (e.g. a hub) experience different durations of downtime and recovery, and how the post-disaster dynamics vary for various port specialisations (e.g. containers versus raw materials).

3.7 Conclusion

Ports are important nodes in the global trade network, but given their location in coastal and riverine areas, they are vulnerable to the impacts of natural disasters. Although much work has been concentrated on modelling port disruptions, various modelling assumptions (such as the duration of disruption, the amount of port substitution, single versus multiple port disruptions and the ability to recapture cargo flows) have not yet been challenged against empirical evidence. In this paper, we have analysed 141 incidences of port disruptions due to natural disasters across 74 different ports globally. Using vessel tracking data (AIS), we provide empirical evidence of the dynamics of port functioning before, during and in the aftermath of port disruptions.

In our sample of port disruptions, median port disruptions equal six days (five days) for ports that have been closed (have not been closed) with a 95^{th} percentile of 22.2 days (11 days). However, some incidences of longer disruptions occur, mainly associated with damage to hinterland infrastructure that prevent the port from fully functioning. Moreover, the ability to recovery from disasters also varies strongly per port and event. On top of that, we find a relationship between the magnitude of an event and the duration of the disruption for U.S.A. ports. Most extreme events tend to close, or affect, multiple ports simultaneously, which can affect the spare capacity at potential substitution ports.

Therefore, freight assignment models that simulate the distribution of freight after single port closures should consider scenarios of multiple port closures. We find little evidence of port substitution happening, most likely associated with the aforementioned simultaneous disruptions, and the short duration of the events considered that makes substitution not viable given physical (e.g. draught), infrastructure (e.g. port equipment, hinterland connection) and contractual constraints (e.g. contracts carriers and terminal operators). On the contrary, production recapture seems a more favourable adaptation option in case of relatively short disruptions (order few days), although a port's likelihood to recapture production depends on the utilisation rate of ports and ability to temporarily increase its capacity.

Future research should complement our disaster database with more disasters and disaster-related parameters that can be used to better identify what drives the duration of port disruptions and resilience of ports. Combining AIS data with other data sources (e.g. customs data) or modelling approaches (e.g. input-output modelling) can provide a more holistic view of the wider supply-chain impacts and recovery due to port disruptions, and how this varies among different types of ports and geographical locations. AIS-derived data can further complement modelling studies to better approximate model parameters and validate the results.

In conclusion, port disruption varies strongly depending upon the port and event, and the dynamics are shaped by various actors involved in minimising the potential negative consequences of port disruptions throughout the supply-chain. Empirical observations of port disruptions are vital sources of information for risk management purposes of ports and supply-chains to better approximate the extent of the disruption, its drivers, and the potential resilience of the port and maritime network.

4 A SYSTEMIC RISK FRAMEWORK TO IMPROVE THE RESILIENCE OF PORT AND SUPPLY-CHAIN NETWORKS TO NATURAL DISASTERS

Chapter 4 presents a new global systems framework of the coupled port, maritime and economic networks, which can be used to analyse systemic risks to these interconnected system components. This framework will form the basis for the following chapters.

Paper: Verschuur, Pant, Koks and Hall (2022), A systemic risk framework to improve the resilience of port and supply-chain networks to natural hazards, *Maritime Economics and Logistics*, doi:10.1057/s41278-021-00204-8

Contributions: Jasper Verschuur: Conceptualization, Methodology, Formal analysis, Writing – Original Draft, Writing – Review & Editing, Visualization. **Raghav Pant:** Writing – Review & Editing**. Elco Koks**: Writing – Review and Editing **Jim Hall:** Writing – Review and Editing.

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.

4.1 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, 2022) (Chapter 5). Apart from their trade facilitation function, ports often serve as important hubs for industry 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 within, or 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 damages 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 damages 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 as a result of 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, which 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) (Chapter 3), causing bottlenecks to 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 (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 a risk analysis framework 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; Y. 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 that 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 their 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 spill-over 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 to port networks.

4.2 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 their spatial extent and economic linkages, which encompass different subnetworks that interact with each other, as shown in Figure 4.1. At the top of the hierarchy, the maritime transport network can be schematised as ports (nodes) and global transportation routes (edges) (Figure 4.1a). The hinterland transport network (Figure 4.1b) 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 4.1c), with the critical infrastructure assets located either within the port domain, or within a close proximity to the port. The supply-chain network depends 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 and Singapore).

Climate-related risks can disrupt individual nodes and edges in the different network layers of Figure 4.1 and thereby directly or indirectly affect operations, resulting in economic losses. In a traditional risk analysis framework, risk is often defined and expressed in terms of asset damages, 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). The traditional risk analysis framework ignore 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 their hinterlands and the freight flows that use certain transportation 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 macroeconomic 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) estimated that a 90-day disruption to the ports of Arthur and Beaumont (United States) can cost up to US$ 167 billion. Although methodologies to estimate the wider macroeconomic 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 materialise, 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, among others, on the 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 spill-overs increases in size when going from local to global (see Figure 4.1).

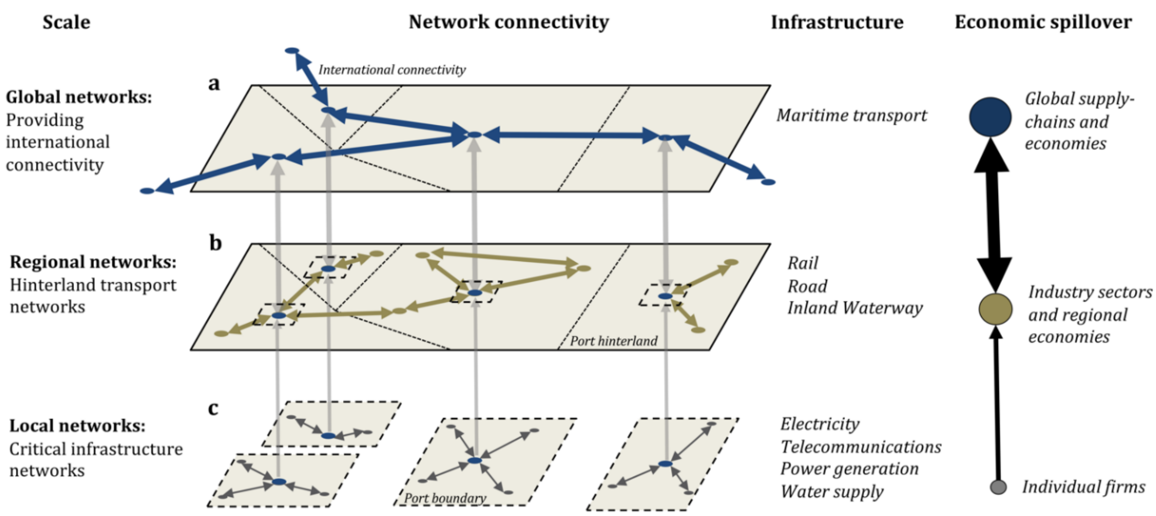

Figure 4.1: The multi-scale port framework depicting the local, regional and global networks that ports are embedded in.

4.3 Critical infrastructure network failure propagation

The interdependency of the critical infrastructure network components within port boundaries may affect port operations directly and indirectly. In Figure 4.2, one 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)dependent 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 targeted Transnet's IT network, a company managing rail, port and pipeline infrastructure in South Africa, which 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 in close proximity to, the port area.

Traditional risk analysis frameworks generally encompass overlaying the geospatial hazard data (e.g., flood map, earthquake severity map) with the location of assets within the port domain (together estimating the exposure of such assets). This is combined with so-called vulnerability, or fragility, curves that define how a given hazard severity at the location of exposed assets translate into a fraction of damage (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 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 analyses 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 losses 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 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 an infrastructure network model in which port operations were dependent on the telecommunications network. 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 increasingly 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 4.2), 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).

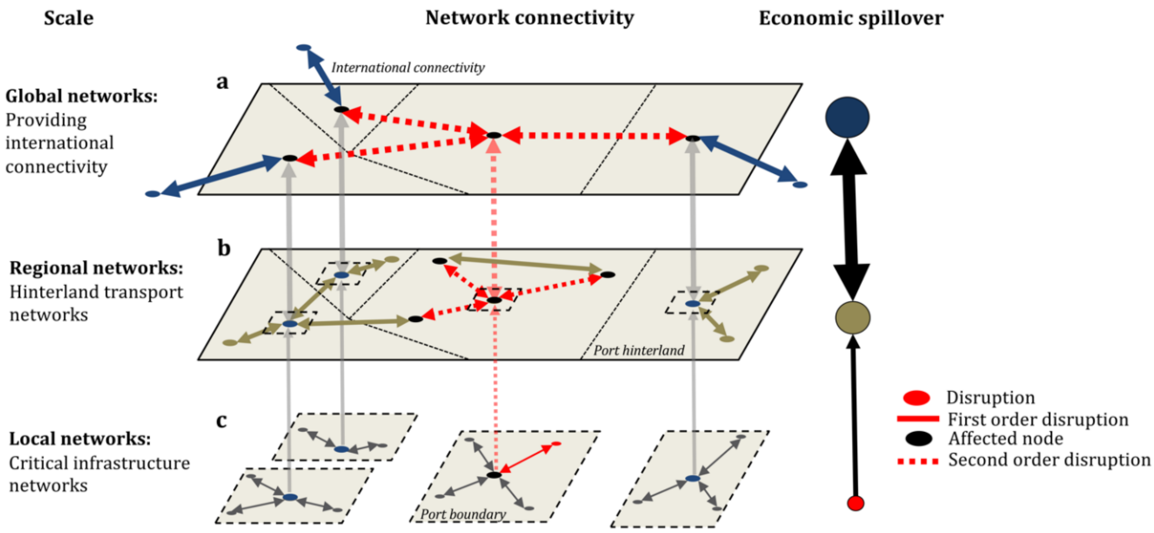

Figure 4.2: The multi-scale port framework showing how a local infrastructure failure, disrupting a port, can further propagate up to the connected networks.

4.4 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 4.3, 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 ports of Louisiana and Baton Rouge (Verschuur, Koks and Hall, 2020) (Chapter 3). 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 low flow conditions 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 4.3).

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 highways 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 roads 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 waterway (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 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 Figure 4.3) 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 in quantifying the costs of rerouting and identify where 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 macroeconomic 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.

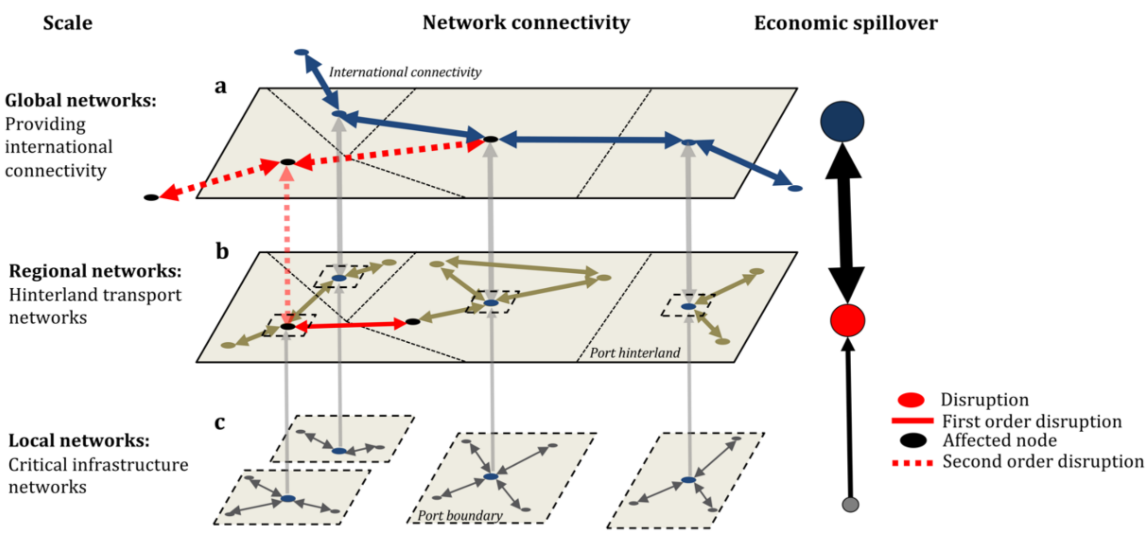

Figure 4.3: The multi-scale port framework showing how a hinterland transport disruption can further propagate horizontally to connected ports, and vertically to other ports.

4.5 Maritime transport network failure propagation

Disruption to the global maritime transport network (MTN) (either to a port or the transport route) can cause a propagation to topologically connected ports and may cause a re-organisation of the network (Figure 4.4). 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 at once (shown in the second-order impacts in Figure 4.4), 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 macroeconomic losses, should be added to the analysis, allowing one to combine the likelihood of port disruptions with the resulting economic repercussions. Third, one should characterise 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, Novati, *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, 2022) (Chapter 5), the potential for widespread economic spill-overs 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 within 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. Similarly, large-scale macroeconomic 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.

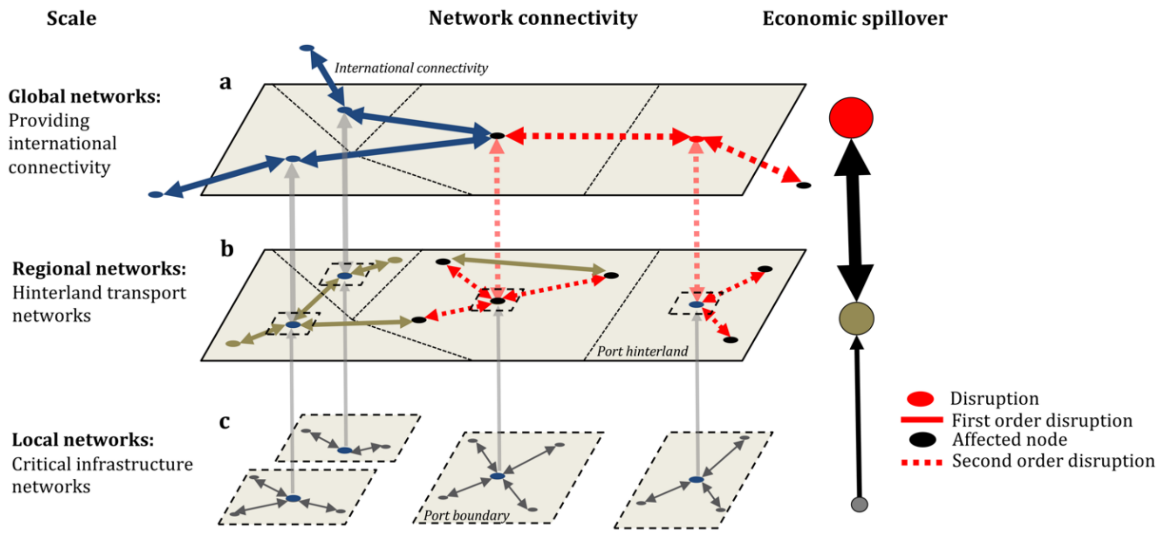

Figure 4.4: The multi-scale port framework showing how a port disruption can further propagate horizontally to connected ports and hinterland areas.

4.6 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 magnitude of the 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) (Chapter 3). 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 could source products from alternative suppliers, 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, on a network-level, 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.

4.7 Discussion and conclusion

This article presents a systemic risk framework for the 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 networks -the 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 materialises 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 hazards, 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 proactively 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 identified potential ways forward in quantifying systemic risks.

For the local critical infrastructure risk analysis, ports authorities can expand upon their detailed climate risk and adaptation analysis, if available, 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 of the development of freight models in more data-scarce environments exist as well (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 generally known how much trade flows from one country to another (from bilateral trade data), 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, 2022) (Chapter 5). Similarly, information on 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 an integrated 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, 2021b).

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.

5 PORT'S CRITICALITY IN INTERNATIONAL TRADE AND GLOBAL SUPPLY-CHAINS

Chapter 5 proposes an integrated framework to couple the global maritime transport network to the wider economy through supply-chain interdependencies. It presents several new metrics of the criticality of ports in international trade and for global supply-chains. This is based on a new global maritime transport model developed, which is linked to multi-regional input-output tables to understand the dependencies between ports and the domestic and foreign supply-chains they serve.

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Contributions: Jasper Verschuur: Conceptualization, Methodology, Formal analysis, Writing – Original Draft, Writing – Review & Editing, Visualization. **Elco Koks**: Conceptualization, Writing – Review and Editing, Supervision. **Jim Hall:** Conceptualization, Writing – Review and Editing, Supervision

Data and code availability: All data to reproduce the results of this study are available on Mendeley Data (https://data.mendeley.com/datasets/vzzy3b9gg4/1). The code to run the maritime transport model and quantify the link between ports and supply-chains is available on GitHub (github.com/jasperverschuur/Port_supply_chains).

Abstract: We quantify the criticality of the world's 1380 most important ports for global supply chains by predicting the allocation of trade flows on the global maritime transport network, which we link to a global supply-chain database to evaluate the importance of ports for the economy. We find that 50% of global trade in value terms is maritime, with low income countries and small islands being 1.5 and 2.0 times more reliant on their ports compared to the global average. The five largest ports globally handle goods that embody >1.4% of global output, while 40 ports add >10% of domestic output of the economies they serve, predominantly small islands. We identify critical cross-border infrastructure dependencies for some landlocked and island countries that rely on specific ports outside their jurisdiction. Our results pave the way for developing new strategies to enhance the resilience and sustainability of port infrastructure and maritime trade.

5.1 Introduction

Maritime transport is considered the backbone of international trade and the global economy (Robinson, 2002; Hesse and Rodrigue, 2004; UNCTAD, 2021). With ports supporting the integration of production centres and consumer markets across borders (Notteboom, Pallis and Rodrigue, 2021b), there are large dependencies and feedbacks between changes in the size and structure of the economy (e.g. trade composition, supply-chain structure) and the expected freight flows through specific ports (Halim, Kwakkel and Tavasszy, 2016; Walsh *et al.*, 2019). Similarly, changes (e.g. new infrastructure investments) or disruptions (e.g. port closures) to the maritime transport network can have implications for supply-chains across multiple countries and industries (Verschuur, Pant, *et al.*, 2022) (Chapter 4).

The maritime transport and global supply-chain networks interact with one another on different spatial scales, with recent events illustrating the tight coupling between the two. On the largest spatial scale, the global trade network, the demand for maritime trade is driven by countries' demand for trade, those countries supplying this trade, and the share of trade being maritime (i.e. modal split). Hence, relative changes in freight flows reflect changes in trade demand, supply and modal split. The COVID-19 pandemic, which affected port operations across the world, changed both demand and supply patterns simultaneously (Notteboom, Pallis and Rodrigue, 2021a). On the one hand, this disrupted maritime transport and supply-chains due to factory shutdowns, port closures and labour shortages (Verschuur, Koks and Hall, 2021a), while on the other hand this led to large trade bottlenecks at many ports due to shifting demand patterns (Celasun *et al.*, 2022). Freight demand on the underlying maritime transport network, consisting of maritime routes that connect ports, is determined by the geographical demand for transport services and the network structure of system. For certain commodities this network is known to be more centralised (e.g. containers) while for others this is more decentralised (e.g. bulk transport) (Kaluza *et al.*, 2010). The 2021 Suez blockage highlighted how a large shock to a specific route within the maritime transport network could affect multiple ports across the globe, and eventually supply-chains depending on these ports (LaRocco, 2021). Ultimately, trade flows handled at the port serve supply-chains across different hinterlands, either directly (e.g. firm directly receiving goods from ports) or indirectly (e.g. firm depending on other firms that receive goods from ports). For instance, Hurricane Katrina (2005), shutting down major Louisiana ports, led to large disruptions to the global grain supply, resulting in export losses for the United States, which rippled to dependent supply-chains globally and raised commodity prices (Trepte and Rice, 2014; Rousset and Ducruet, 2020).

The criticality, that is the systemic (i.e. network-based) importance, of ports for the economy is often framed in terms of the absolute amount of trade flowing through a port, its network characteristics within the maritime transport network (e.g. node centrality) (Kaluza *et al.*, 2010; Ducruet and Zaidi, 2012; Li, Xu and Shi, 2014), or in terms of its contribution to the local or regional economy (e.g. regional employment and value-added) (Merk, Manshanden and Droes, 2013). These framings, however, ignore the primary function of ports as the physical infrastructure that connects supply-chains across countries (Robinson, 2002; Notteboom, Pallis and Rodrigue, 2021b), and therefore fail to provide a comprehensive picture of the dependencies and feedbacks between ports and the economy.

Establishing a fine-scale representation of how each individual industrial sector, globally, makes use of maritime transport, and, on the other hand, how individual ports are critical to global supply chains can help us rethink the importance of ports, which can be informative for different disciplines. For instance, it would enable a better understanding of the geographical distribution of physical trade flows across supply-chains (Venables, 2005; Wenz *et al.*, 2015), connect environmental footprints with commodity flows (Godar *et al.*, 2015; Moran *et al.*, 2020), predict future port demand (in terms of volume and space required) as economies grow (Hanson and Nicholls, 2020), help allocate maritime emissions (~2.6% global greenhouse gas emissions in 2012) to countries and sectors (Schim van der Loeff, Godar and Prakash, 2018; Wang *et al.*, 2021), and assess the potential supply-chain losses due to maritime transport disruptions (Rose and Wei, 2013; Verschuur, Koks and Hall, 2020).

So far, a number of macroeconomic studies have examined the evolution of international trade and supply-chain interconnectivity (Los, Timmer and de Vries, 2015; Maluck and Donner, 2015; Amador and Cabral, 2017). These analyses are backed by advances in the provision of Multi-Regional Input-Output (MRIO) tables that describe the inter-, and intra-industry dependencies within countries and between countries (Lenzen *et al.*, 2012, 2017; Dietzenbacher *et al.*, 2013; Timmer *et al.*, 2015). Although MRIO tables provide extensive data on inter-, and intra-industry trade flows, at national and regional scales, it does not provide insights into the domestic and international transportation systems that are used for these trade flows. Another strand of literature has analysed the network structure and evolution of maritime transport networks through a complexity science lens (Kaluza *et al.*, 2010; Li, Xu and Shi, 2014; Ducruet, 2016, 2017; Wang *et al.*, 2016; Kojaku *et al.*, 2019; Peng *et al.*, 2019; Xu *et al.*, 2020). This research, however, focused solely on the shipping connections between ports, without incorporating information on the goods that are carried by maritime vessels, where goods are coming from and going to, and how goods are used in the economy. Hence, to date, there is still a spatial mismatch between information describing the structure of the global economy (i.e. global trade and supply-chain data) and a bottom up representation of the transportation network used (i.e. observed maritime transport flows) to facilitate this economic structure.

Here, we present a new modelling framework that provides a comprehensive understanding of the different dimensions of the criticality of ports for domestic and global economies (e.g. on the trade, transport and supply-chain level) that are not captured in aggregate port-level trade statistics. To do this, we provide a globally consistent assessment of the links between ports and maritime trade, the transport networks they utilise (1380 ports across 207 countries), and the supply-chains they serve (1298 ports across 176 countries) (see Methods). This is achieved by first estimating the fraction of maritime trade in all bilateral trade flows and feeding this into the newly developed Oxford Maritime Transport (OxMarTrans) model that simulates the maritime and hinterland routes taken to transport maritime trade flows. The trade flows going through ports are then linked to a global supply-chain database (EORA MRIO tables (Lenzen *et al.*, 2012)) to quantify the links and feedbacks between ports and the economy.

We find that around 50% of global trade (in value terms) is maritime, which reaches up to 76% for the mining and quarrying sector. Low income countries and small island developing states (SIDS) rely disproportionally on maritime trade; their maritime import fraction is 1.5 and 2.0 times higher, respectively, than the global average. Every USD flowing through a port is associated with 4.3 USD, on average, of economic activity. We identify ports being critical for the global and domestic economy, showing how the top five macro-critical ports all handle goods that contribute >1.4% to the global economy**,** while 40 ports handle goods that represent >10% of the value of the domestic economies they serve (i.e. domestically critical ports). In addition, we find that every 1000 USD increase in final demand (i.e. the goods needed to meet final consumption and exports) results in a median 84.6 USD increase in maritime imports across the ports that serve these economies, with 30 individual ports experiencing >100 USD increase. Our results pave the way for a better understanding of the key links, dependencies and feedbacks between port, the maritime infrastructure network and the global economy, which is essential information for sustainable infrastructure planning.

5.2 Results

5.2.1 Overview

The results summarise the model output for the different layers; the trade network layer, the transport network layer, and the port supply-chain layer. These three layers are conceptualised in Supplementary Figure A2.1. The trade network layer results discuss the output of the global modal split model (i.e. the distribution of trade flows across transport modes) that quantifies the variations in countries' dependencies on maritime trade as a fraction of total trade on a commodity level. The transport network layer results outline several output of the OxMarTrans model**.** The OxMarTrans model simulates the route choice of millions of maritime freight flows between 3400 (subnational) regions across 207 countries on the hinterland and maritime transport network. The output includes the aggregate global freight flows on the transport network and through the two main canals (Suez and Panama), the dependency of countries on maritime infrastructure in foreign jurisdictions through land-based connections and transhipments, the port-level trade flows, and the trade flow distribution across all ports. To quantify the domestic and global economic dependencies on trade flows through ports (i.e. the port supply-chain layer), we use the EORA MRIO tables (Lenzen *et al.*, 2012) that we extend to the port-level to link the commodities that flow through ports to the global supply-chains they serve. Two metrics are constructed to capture these dependencies; (1) the port-level output coefficient (PLOC) and (2) the port-level import coefficient (PLIC). The base year considered in this analysis is 2015, which is the latest available year in the EORA MRIO database (at the time of writing). Throughout this study, we adopt a 11 sector industry classification in line with the EORA MRIO to evaluate differences in criticality between sectors (Supplementary Table A2.1).

5.2.2 Share of maritime transport in global trade

Within the trade network layer, the amount of maritime trade between countries is determined by the absolute value of trade across all modes between country pairs and the share of this being maritime. Our transport modal split model estimates the share of maritime trade for around eight million bilateral trade flows globally on a commodity level (HS6). It should be noted that in this study the mode of transport is defined as the dominant transport mode (longest distance) in the supplier-consumer connection, which means that landlocked countries can still rely on maritime transport (see Methods).

We estimate that 9.4 billion tonnes of trade, equivalent to around 7.6 USD trillion in value terms, was maritime in 2015. This number corresponds well with the estimated 9.96 billion tonnes of trade being discharged in ports in 2015 as reported by UNCTAD (UNCTAD, 2017b). The share of maritime trade in global trade is around 75% in terms of weight and 50% in terms of value. However, large differences exist between sectors. For instance, while 75.7% (86.0%) of Mining and Quarrying (sector 3) products are transported by means of maritime transport in value (weight) terms, most manufacturing sectors (sector 4 to 11) transport only 40% – 57% (53% – 60%) of their trade in value (weight) terms using maritime transport.

Figure 5.1 shows the percentage of maritime transport in total imports (Figure 5.1a) and total exports (Figure 5.1b) per country, while Supplementary Figure A2.2 and A2.3 display the same results per economic sector. The dominance or absence of maritime transport for trade is mainly determined by the geographical location of trading partners (e.g. distance, island state), the presence of alternative (fast and cheaper) modes, the value to weight ratio of the commodities, and the standard of living of the importing country (e.g. quality of logistics services) (Martínez, Kauppila and Castaing, 2015).

As can be seen from Figure 5.1, Caribbean islands, countries in Oceania and some countries in Africa (e.g. Somalia, Nigeria, Gabon) rely disproportionally on maritime transport for both imports and exports (Figure 5.1a-b). European countries, in particular landlocked countries (e.g. Romania, Hungary, Switzerland), have a much lower share of maritime transport, mainly due to the large trade flows between European countries that use road, rail and inland waterway transport to move goods over relatively short distances (Cristea *et al.*, 2013; Jonkeren *et al.*, 2014). Middle-Eastern (Saudi Arabia, United Arab Emirates) and South American (e.g. Brazil, Colombia) countries rely more on maritime transport for their exports compared to their imports. These countries mainly export raw materials (e.g. oil, coal, grain) which is predominantly shipped by maritime vessels, but import a more diversified mix of goods that are transported by multiple modes. Small Island Developing States (SIDS) rely disproportionally on maritime transport, with 86.5% of imports and 79.8% of exports being maritime, thus almost twice as much as non-SIDS countries. SIDS are often served by a few maritime transport routes and experience high transportation costs (Arslanalp, Koepke and Verschuur, 2021), making reliable maritime transport services critical for the well-functioning of SIDS' economies.

Figure 5.1c shows the share of maritime transport in total and sector-specific imports grouped by the income level of countries (using the 2021 World Bank classification). Low income countries import on average 1.5 times more by means of maritime transport compared to high income countries (68% versus 45%). The difference is largest for the manufacturing sectors (sector 8 to 11), having maritime shares 1.5 – 1.8 times higher than high income countries. This difference can be explained by the fact that low income countries often trade low value bulk goods, for which maritime transport is the only viable option, and relatively few high valued goods that are more often transported by aeroplane (Hummels, 2007). Even within the same continent, such as in Africa, maritime transport is often the only feasible mode of transport for certain goods as the road infrastructure lacks the reliability and capacity for efficient trucking, and border crossings can be time consuming (Buys, Deichmann and Wheeler, 2010; UNCTAD, 2020). Therefore, the integration of low income countries into complex manufacturing supply-chains, which critically depend on just-in-time logistics services (Coe, 2014), could be hindered by their overreliance on maritime transport, which is considerably slower than air transport (Hummels and Schaur, 2013; Ansón *et al.*, 2020).

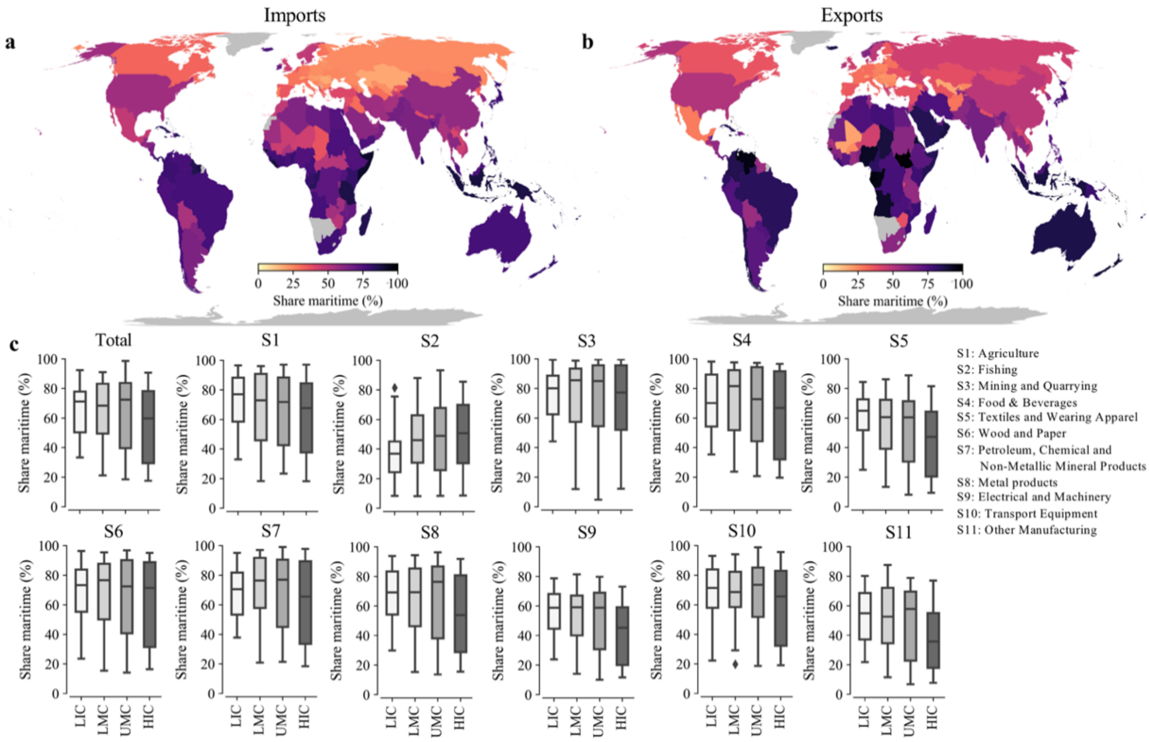

Figure 5.1: The share of maritime transport in global trade**.** (a-b) Country's percentage of maritime imports (a) and exports (b) based on the 2015 trade network. (c) Boxplots of the percentage maritime imports per economic sector with countries grouped by income level (based on the World Bank income classification). LIC: Low income countries, LMC: Lower middle income countries, UMC: Upper middle income countries, HIC: High income countries.

5.2.3 Global maritime transport flow allocation

The maritime transport network, consisting of ports and maritime routes transporting goods using different vessel types (e.g. tankers, containers), connects the locations of production to their demand markets. The OxMarTrans model predicts which ports and maritime routes, including locations of transhipments, are being used to transport the maritime trade flows between each country pair and per economic sector (see Methods). The underlying hinterland and maritime consists of 1380 ports, with the port connections and maritime network capacities incorporated in the model based on a dataset of observed ship activities from Automatic Identification System (AIS) data (Verschuur, Koks and Hall, 2021a). The OxMarTrans model therefore helps to identify the spatial connectivity of ports; the maritime subnetwork that is used to transport goods from and to a specific port (we show the spatial connectivity for nine ports in Supplementary Figure A2.4).

Globally, to meet maritime trade demand, we estimate that 90.5 trillion tonnes-km of freight is transported across sea and an additional 33.4 trillion tonnes-km over land to connect hinterlands to ports. The maritime freight predicted by the model is consistent with the 84 trillion tonnes-km estimated by UNCTAD (UNCTAD, 2017b). 43% of the total maritime tonnes-km is attributed to the Mining and Quarrying sector (sector 3) alone, while the manufacturing of Electrical and Machinery products (sector 9), Transport Equipment (sector 10) and Other Manufacturing goods (sector 11) together account for only 2.7% of total tonnes-km. Supplementary Figure A2.5 shows the total throughput (sum of import, export and transhipment) per port and estimated flows on the maritime transport network, while Supplementary Figure A2.6 shows a similar result per sector.

Many countries depend on the transport of goods passing the Suez or Panama canal. In total, our model predicts that around 1.1 USD trillion (13.9% of maritime trade) and 0.49 USD trillion (6.2% of maritime trade) pass the Suez and Panama canal, respectively, in 2015 in line with official statistics (see Supplementary Note A2.3). For the Panama canal, ports in the Gulf of Mexico, the west coast of South America, and parts of East Asia rely directly on goods being shipped through the canal (Figure 5.2a). The Suez canal is important for trade going from and to the Asia and Europe. On the east of the canal, the ports of Singapore, Jeddah, Colombo, Mina Jebel Ali are most dependent on the Suez canal, while on the west of the Suez canal the ports of Piraeus, Rotterdam, Marsaxlokk and Algeciras rely most on it (Figure 5.2b).

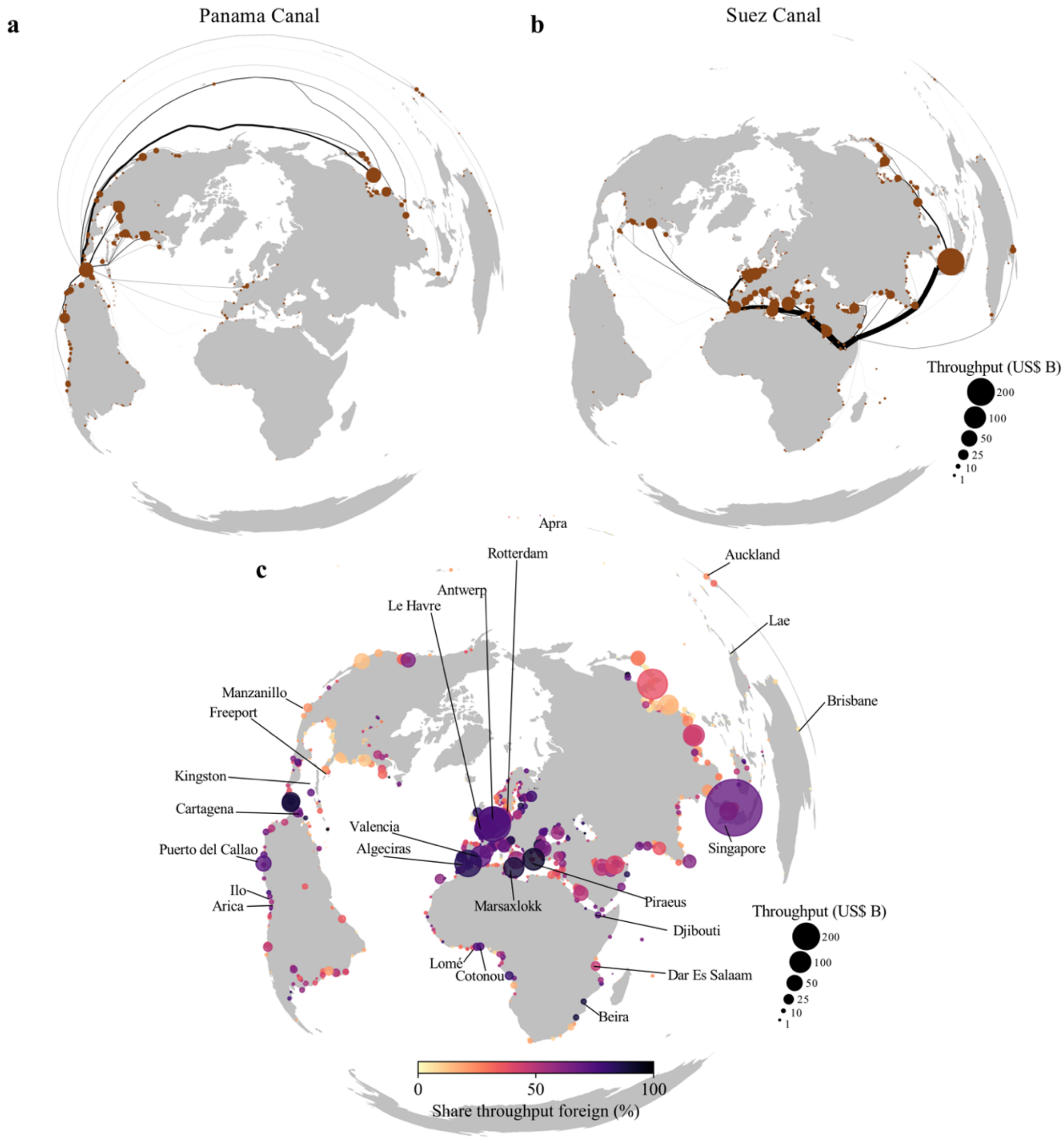

Figure 5.2: Cross-border maritime infrastructure dependencies. (a) The port-level throughput (import, exports and transhipment) that comes from or goes to ports by passing the Panama canal. (b) Same as (a) but for the Suez canal. (c) The share and absolute value of port-level throughput that is linked to a foreign economy, either because of transhipment or a land-based connection. Some regionally important ports in terms of foreign dependencies are annotated.

5.2.4 Cross-border maritime infrastructure dependencies

Both landlocked and maritime economies rely on maritime infrastructure in other countries because they either use ports in neighbouring countries to import or export goods, or they use transhipment services to ship goods from origin to destination. For instance, around 28% of the world's container throughput in 2012 involved transhipment, where containers unloaded from a deepsea vessel are being transhipped to another deepsea vessel or a smaller vessel (i.e. feeder vessels) to serve otherwise unconnected port pairs (Notteboom, Parola and Satta, 2019).

Using the OxMarTrans, we estimate that approximately 16.4% of global port throughput (in value terms) is transhipped, while 19.4% of port throughput are imports to or exports from foreign countries connected via the hinterland transport network. Figure 5.2c shows the fraction of port throughput being foreign per port. In absolute terms, large transhipment hubs (Singapore, Algeciras, Valencia and Marsaxlokk) have a high share of foreign throughput. Additionally, ports in the Le Havre-Hamburg range (Le Havre, Antwerp, Rotterdam, Bremen) handle the largest amount of foreign import and export value, as they compete for trade going to, and coming from, the Central European hinterland (Zondag *et al.*, 2010).

Regionally, some ports play key roles in serving landlocked countries or island states (see highlighted port in Figure 5.2c). In Africa, for instance, the port of Djibouti handles almost all of Ethiopia's maritime trade, the ports of Dar Es Salaam (Tanzania) and Beira (Mozambique) are essential for landlocked countries in Sub-Saharan Africa, while the port of Lomé (Togo) and Cotonou (Benin) are key for Western-African landlocked countries. In South America, the ports of Arica (Chile) and Ilo (Peru) handle the majority of maritime trade of Bolivia, while Puerto del Callao (Peru) is an important transhipment hubs for South America. In Oceania, several ports (e.g. Brisbane, Auckland, Apra, Lae) serve as important transhipment hubs for Pacific island economies, with a similar observation for key regional transhipment hubs in the Caribbean region (see Figure 5.2c).

5.2.5 Distribution of trade flows per port

Several factors determine the total maritime trade flows going through ports (e.g. maritime connectivity, logistics services, presence of hinterlands). Figure 5.3a-b show the distribution of imports (Figure 5.3a) and exports (Figure 5.3b) across all trade flows, with the top ten largest ports annotated. We also show the global core ports, defined as those ports responsible for importing or exporting 50% of global trade (black edge colour). Core importing ports are located in North-America (Los Angeles-Long Beach, New York-New Jersey), Western Europe (Rotterdam), the Middle-East (Mina Jebel Ali) and Asia (Singapore, Shanghai) that serve the populated hinterlands (so-called gateway ports (Xu *et al.*, 2020)) or industrial and logistics hubs. Among the core exporting ports are specialised ports that are critical for the exports of agricultural products (Vancouver, New Orleans, Santos), petrochemicals (Houston, Singapore, Rotterdam), iron ore (Port Hedland and Dampier), electrical and machinery manufacturing (Shanghai, Busan, Kaohsiung), car manufacturing (Ulsan, Nagoya, Bremerhaven), and oil and gas (Ras Tanura, King Fahad Industrial Port).

Trade is highly concentrated in a relatively small number of core ports. The trade unevenness expresses the number of ports that handle 10%, 50% and 90% of trade. Only 4 (3) ports are responsible for 10%, 56 (48) ports are responsible for 50%, while 378 (366) ports are accounting for 90% of global maritime imports (exports) (Supplementary Table

A2.2). This underlines that from a global perspective, the maritime transport network consists of a small number of core ports and a large number of secondary (i.e. periphery) ports.

The aggregate results do hide the importance of certain ports on a sectoral level. Figure 5.3c shows the geographical location of the core importing and exporting ports per sector, showing a clear geographical clustering of trade flows that are either connected to important demand markets (Notteboom and Rodrigue, 2008), or closely located to large sector-specific industry clusters (Notteboom and Rodrigue, 2008). Agriculture trade (sector 1) has clear origin ports in the United States, Brazil and Argentina, serving ports in Europe and across Asia. The import and export hotspots of Mining and Quarrying (sector 3) and Food and Beverages (sector 4) products are more spread across the globe, reflecting the export specialisation of different regions (e.g. oil in Middle-East, iron ore and coal in Australia, food products in Indonesia and Malaysia). The Wood and Paper manufacturing (sector 6) sector has large exporting ports in Scandinavia, the United States and China, that export timber products to ports in the United Kingdom, Japan and the Middle-East. Metal products (sector 8) are exported through Chinese, South African and Chilean ports and supplied to the Middle-East, South-East Asia and the United States. The remaining manufacturing sectors (sector 5, 9-11) all have large exports in ports in Western-Europe, East-Asia and the United States, with goods imported in ports in the Middle-East, Australia and parts of South America.

The trade unevenness differs considerably per sector (see Supplement Table A2.2). The largest unevenness is found for the exports of Textiles and Wearing Apparel (sector 5), manufacturing of Transport Equipment (sector 10) and Other Manufacturing (sector 11) while the lowest level of trade unevenness is found for the imports of Agricultural products (sector 1), Food and Beverages (sector 4), and Petroleum, Chemical and Non-Metallic Mineral products.

These sectoral heterogeneities do not only reflect the differences in the clustering of industries, but also economies of scale present in the transport of some goods (Ducruet, Itoh and Joly, 2015; Ducruet and Itoh, 2016). For example, while for some highly concentrated sectors the vast majority of goods will be transported between a subset of core ports, other less concentrated sectors will use a more decentralised transport network. These sectoral differences reinforce the results found in previous studies that analysed the characteristics of networks of different types of maritime vessels (which are indicative of the sector) and found similarly critical differences between these vessel networks (Kaluza *et al.*, 2010; Ducruet, 2017; Xu *et al.*, 2020).

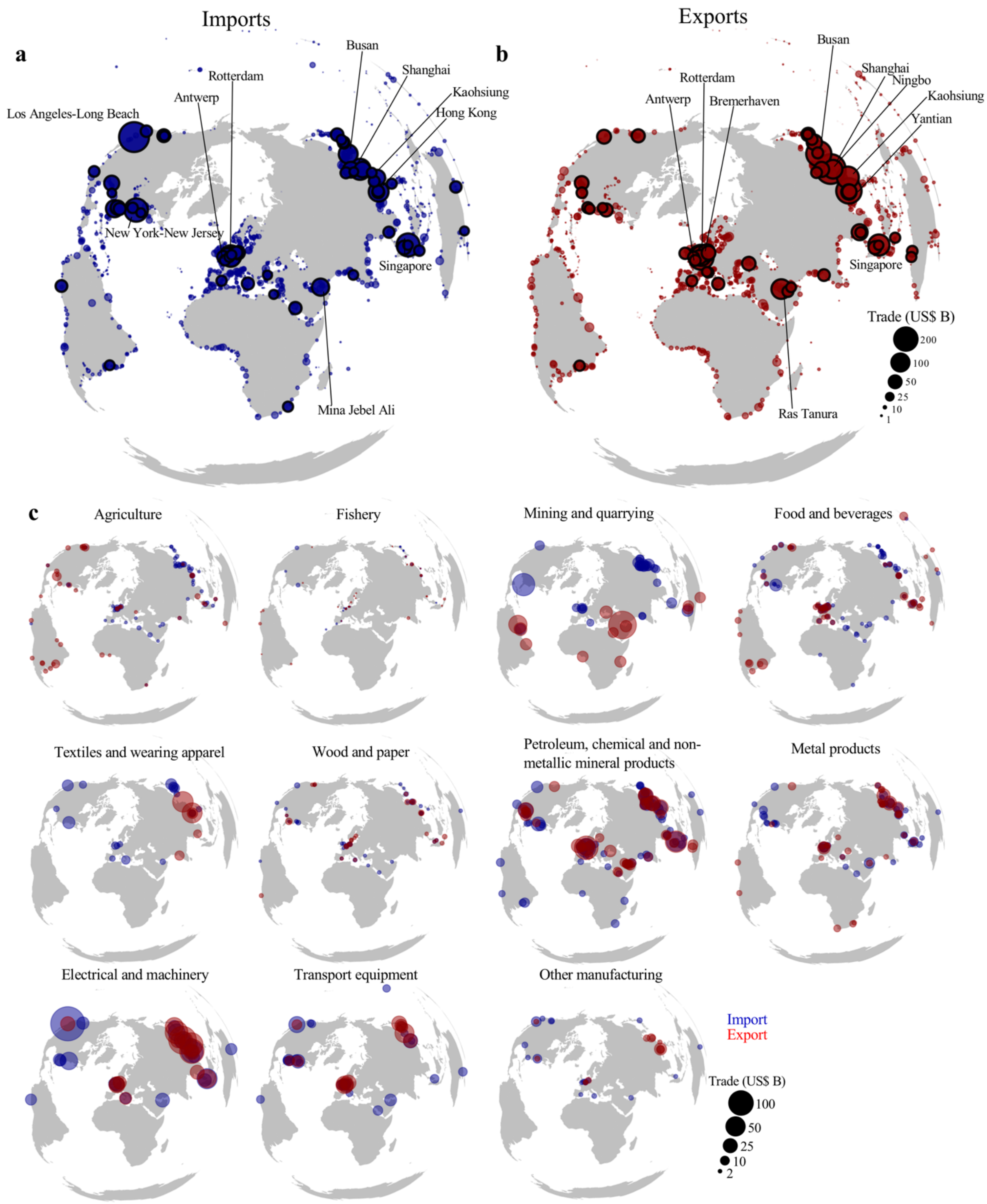

Figure 5.3: The origin and destination ports of trade flows. (a-b) The aggregated imports (a) and exports (b) per port. The core ports are highlighted with the top 10 ports annotated. (c) The location of the core importing (blue) and exporting (red) ports per sector.

5.2.6 Port-level output coefficient

Every port is connected to one or multiple supply-chains in the domestic and foreign economies they serve, either through direct (e.g. through firms directly sending or receiving goods from a port) or indirect (e.g. through firms depending on other firms that send or receive goods from a port) economic connections. More specifically, the products that are imported through a port are either directly consumed in an economy or are used in production processes to produce goods for domestic consumption or export. Additionally, goods exported through a port are being used in production processes, or directly consumed, elsewhere. We call this the port supply-chain network. To understand the criticality of the trade facilitation function of ports for domestic and global supply-chains, we developed a metric, called the port-level output coefficient (PLOC), that captures the total industry output and consumption directly or indirectly dependent on the trade flows through a port, either in absolute terms (PLOCA) or relative to the amount of trade going through a port (PLOCR). This is done by removing the trade flows going through a port from the extended MRIO table and quantifying the output changes to the domestic and global economy (see Methods).

In relative terms (PLOCR), every USD of trade going through a port influences on average (5^{th}-95^{th} percentiles) 4.34 (3.84 – 5.03) USD of value in the global economy (Supplementary Figure A2.7). Large relative values are found for ports in East-Asia (e.g. China, South-Korea, Taiwan), which are strongly integrated in global supply-chains, but also for some of the raw materials exporting ports in Australia (e.g. Port Hedland and Dampier) and Africa (e.g. Port of Saldanha), which are important for supply-chains downstream (e.g. firms using intermediate products that are produced using raw materials).

In absolute terms (PLOCA), some ports are important for the domestic economy, while others are more important for the global economy. In some cases, ports are critical for both, as outlined in Figure 5.4a, which shows the top ten most critical ports for the domestic economy and the global economy. The top five most critical ports for the global economy (Singapore, Shanghai, Busan, Rotterdam, Antwerp) all handle goods that directly or indirectly contribute to >1.4% of global industry output. In total, 94 ports are considered macro-critical for global supply-chains, indicating that more than 0.1% of global industry output depends on these ports. 40 ports are considered domestically critical, with over 10% of industry output dependent on trade going through a single port. Examples of some ports that are critical for the domestic economy but negligible on a global scale (dark blue or purple markers Figure 5.4a) are the ports of Port Louis (Mauritius, 26.9% of domestic output), Pointe-a-Pierre (Trinidad and Tobago, 24.9% of domestic output), Reykjavik (Iceland, 23.0% domestic output) and Sitra (Bahrain, 25.3% of domestic output). The ports of Kaohsiung (Taiwan), Hong Kong (Hong Kong), Laem Chabang (Thailand), and Port Klang (Malaysia) (red markers Figure 5.4a) are found to be essential for both the domestic and global economy. A similar figure can be produced for the final consumption needs of countries, with globally and domestically critical ports shown in Supplementary Figure A2.8. Although an overall similar spatial footprint, some ports are more important for meeting final consumption, especially for some small island economies where single ports import over 35% of the country's final consumption requirement. Hence, the tendency to focus on the absolute size of trade going through a port to classify its importance ignores how some smaller ports are still critical for domestic economies.

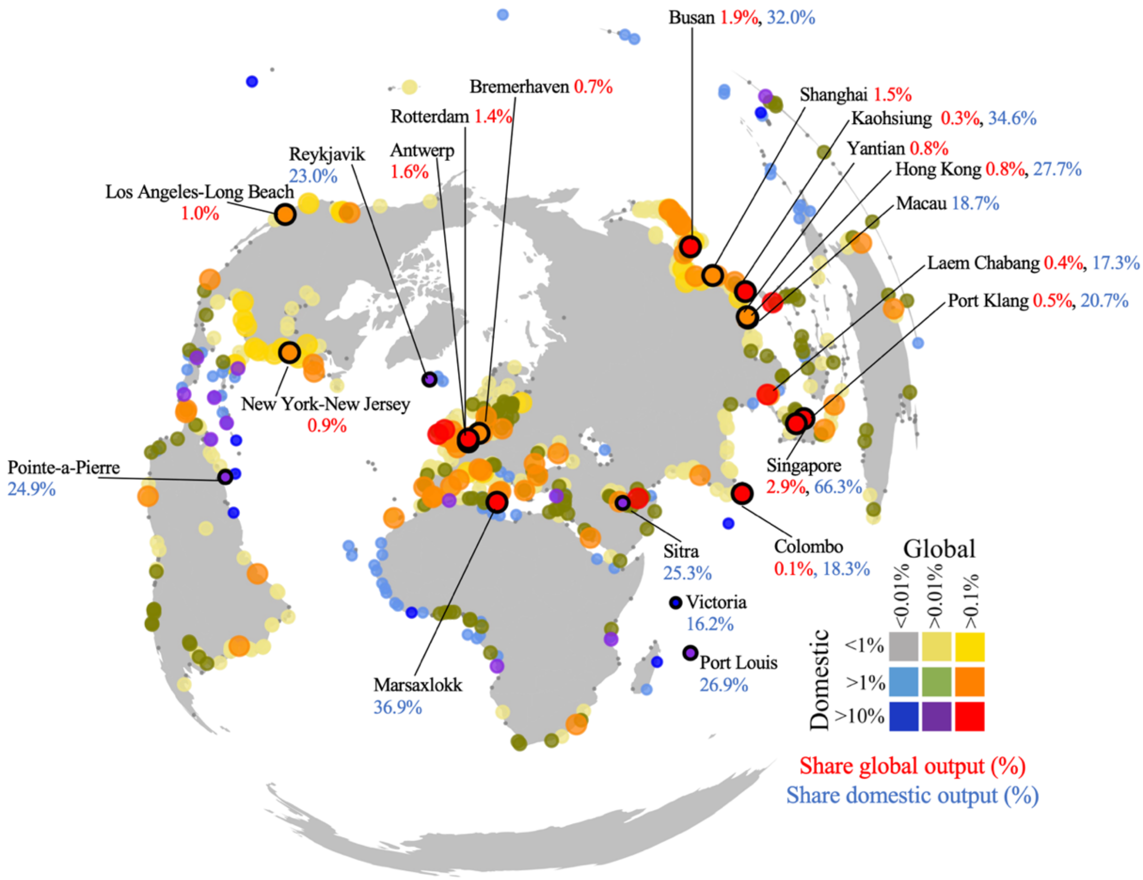

Figure 5.4: Distribution of the domestically and globally critical ports in terms of industry output. The importance of trade flows going through ports in terms of its contribution to the domestic output as a percentage of total domestic output and global output as a percentage of total global output. The ten ports most critical ports in terms of domestic and global output are highlighted together with the associated percentage value (domestic in blue, global in red).

5.2.7 Position port in global supply-chains

To unpack the PLOC metric even more, one can characterise whether the goods that flow through a port are relatively more dependent on domestic or foreign production processes, and relatively more on forward (exporting goods being used in production processes downstream in the supply-chain) or backward linkages (import goods that are produced using production processes upstream in the supply-chain). The relatively importance of these four components determine how ports are positioned differently within the global supply-chain network.

In Figure 5.5, we show the relative importance of port throughput in terms of its contribution to industry output downstream (forward) or upstream (backward) in the supply-chain and the degree to which throughput is linked to domestic or foreign supply-chains. We show the position of a number of ports that are all considered macro-critical but located at opposite ends of the spectrum. The ports of Rotterdam, Singapore and Algeciras have large foreign dependencies, with Rotterdam and Singapore being positioned in the middle of supply-chains (mainly due to their role as petrochemicals hub) and Algeciras more towards the end of supply-chains (given its transhipment of manufactured goods). Shanghai and Bremerhaven, on the other hand, have higher domestic dependencies and larger backward linkages. These ports are highly integrated with domestic manufacturing supply-chains (e.g. car manufacturing for Bremerhaven, and electronics and other manufacturing for Shanghai). The port of Los Angeles-Long Beach has large backward linkages, illustrating that it mainly imports goods at the end of the supply-chain, while Ulsan has large forward linkages as it plays a key role in the exports of domestically produced goods (e.g. vehicles). On the left hand side of the spectrum are ports with mainly forward linkages, implying that they mainly export goods that are used in production stages downstream in the supply-chain, such as Itaqui (iron ore and grains) and Mina Al Ahmadi (oil).

The PLOC metrics illustrate how domestic and global supply-chains are tied to the port, and how ports are positioned differently in the global supply-chain network. Although beyond the scope of this work, this measure could help evaluate the potential losses within supply-chains networks if ports are disrupted by a shock. Moreover it could help allocate maritime emissions embedded in freight flows going through ports to specific supply-chains.

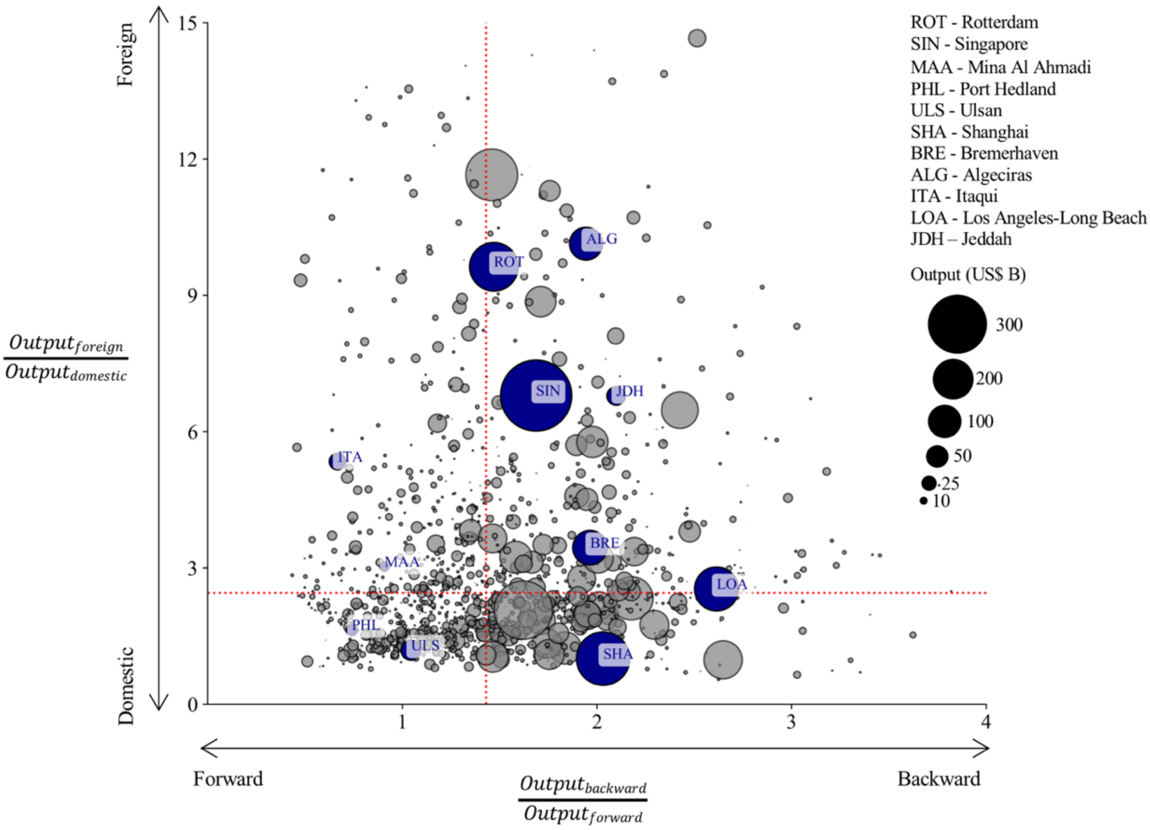

Figure 5.5: The relative importance of forward/backward and domestic/foreign port-industry linkages. The contribution of port-level trade to total output subdivided into forward and backward economic linkages and domestic and foreign economic linkages, capturing the relative importance of the four components. The size of the dot corresponds to the total output linked. The red dotted line depicts the median values across all ports. Ports highlighted in blue and annotated are mentioned in the text.

5.2.8 Port-level import coefficient

As economies grow, and final demand (i.e. domestic consumption and exports) changes in absolute terms and composition, imports through ports are necessary to facilitate this. Due to an increasing fragmentation (i.e. different stages of production in different countries) and globalisation (i.e. global expansion) of supply-chains (Hummels, Ishii and

Yi, 2001; Los, Timmer and de Vries, 2015), the reliance on maritime imports to support final demand has increased. As a complementary metric to describe the feedback between ports and the economy, we use the extended MRIO table to estimate the direct and indirect (through interindustry dependencies) imports per port needed to produce the domestic consumption and exports in the economies they serve. The port-level import coefficient (PLIC, see Methods) quantifies the marginal change in port-level imports for every 1000 USD change in final demand across all economies.

Figure 5.6a highlights the 15 ports with the largest PLIC values. These top-15 ports all have PLIC values of >170 (up to 486), with 27 ports having a PLIC of >100. The ports with the largest PLIC values are relatively small ports serving island nations (e.g. Maldives, Aruba, Mauritius, French Polynesia), but also the port of Dar Es Salaam serving demand in Tanzania and the landlocked African hinterland. Some larger ports that function as important transhipment hubs (Singapore, Kingston, Marsaxlokk and Freeport) also have large PLIC values, indicating that they are not only essential for connecting ports across the region, but also to meet the final demand in their island economies.

Similar as with the cross-border throughput dependencies, some ports are more sensitive to demand changes in foreign economies than their domestic economy (Supplementary Figure A2.9). For instance, some key ports in Africa (Djibouti, Berbera, Cotonou, Maputo) are more sensitive to changes in foreign demand than domestic demand, as they serve landlocked economies that are larger than their own. Similarly, in Europe, large foreign demand sensitivities are found for the ports of Bar (Montenegro) and Burgas (Bulgaria).

In general, larger PLIC values are found for ports in countries that have a limited number of importing ports and have a high overall trade openness, i.e. they rely disproportionally on foreign products to meet their domestic consumption and for use in domestic production processes that are later exported to other countries. To further explore the differences between countries, we aggregate the PLIC values to the economies they serve (country-level import coefficient, CLIC), indicating the USD increase in country-wide maritime imports due to a 1000 USD increase in final demand.

On a country-level, for every 1000 USD increase in final demand, ports that serve that country experience a median (maximum) 84.6 (501.5) USD increase in maritime imports, underlining large differences between countries. SIDS have a 1.5 times higher CLIC compared to non-SIDS countries (Figure 5.6b). Figure 5.6c displays the CLIC across income groups, showing that low income countries have lower CLIC, as they are often less integrated and diverse supply-chains. In general, manufacturing sectors have larger import coefficients, requiring more maritime imports per unit of final demand (Hummels, Ishii and Yi, 2001). For instance, across all countries, the Agricultural (sector 1) and Mining and Quarrying (sector 3) sectors require on average 40 USD of maritime imports for every 1000 USD change in sectoral demand, while some manufacturing sectors (sector 9 – 11) require on average 112 – 153 USD in maritime imports for every 1000 USD change in sectoral demand. Therefore, given that high-income countries are generally more diversified (e.g. higher manufacturing base) and better integrated within global supply-chains, they require more maritime import per USD change in final demand.

The import coefficients (on a port and country level) help to understand how future trade flows through ports will change as countries develop (e.g. demand growth), supply-chains restructure (e.g. better supply-chain integration), and the sectoral composition shifts (e.g. higher manufacturing base).

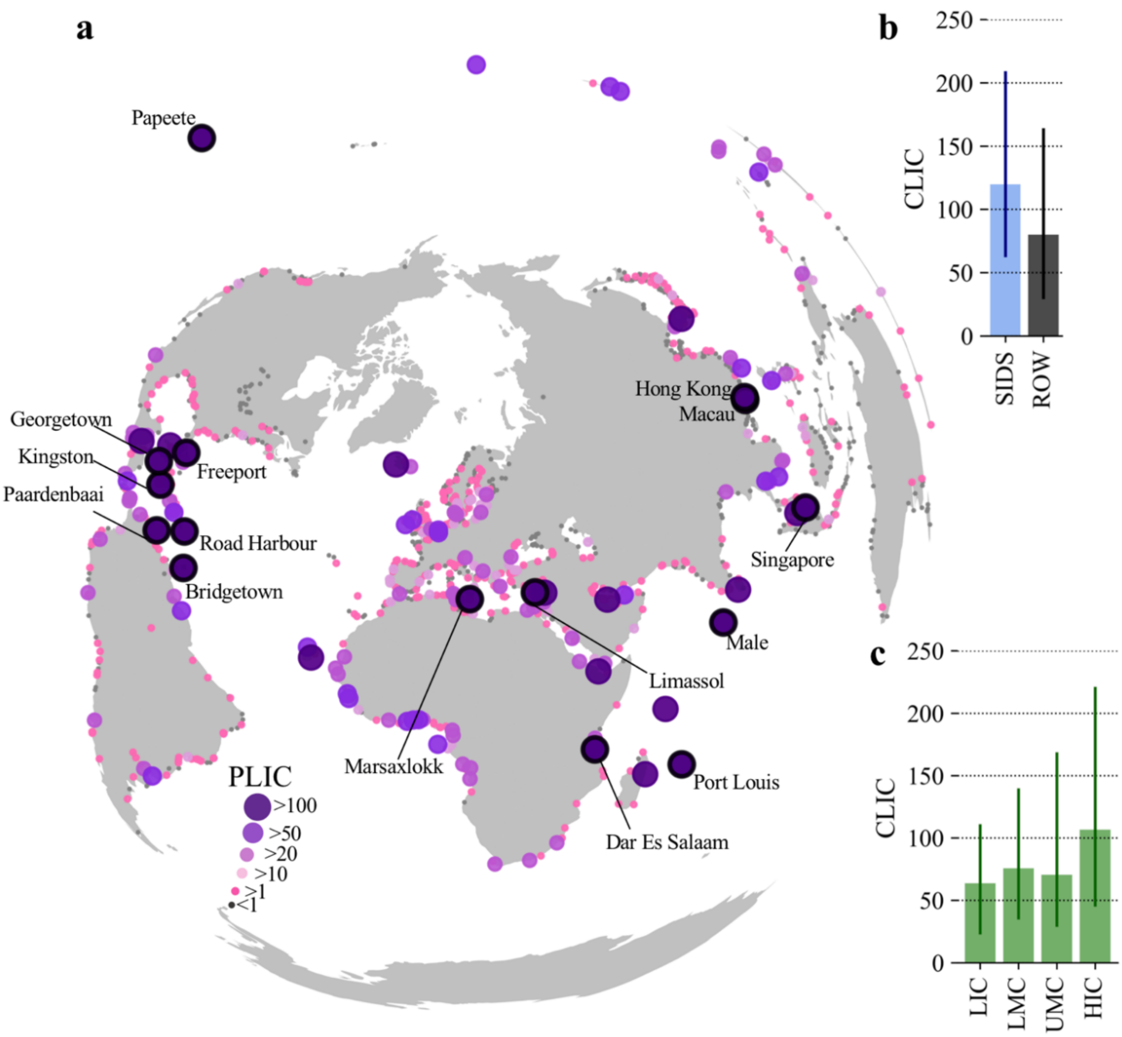

Figure 5.6: Global distribution of the country-level and port-level import coefficient. (a) The global distribution of the port-level import coefficient (PLIC), expressing the USD increase in imports for every 1000 USD increase in final demand. The top 15 ports are highlighted and annotated. (b) The country-wide maritime import coefficient (CLIC) for Small Island Developing States (SIDS) and to the rest of the world. (c) Same as (b) but the CLIC of the countries grouped by income level (based on the World Bank income classification). LIC: Low income countries, LMC: Lower middle income countries, UMC: Upper middle income countries, HIC: High income countries.

5.3 Discussion

This study presents a comprehensively global analysis of the different dimensions of the criticality of 1380 individual ports for the international trade, maritime transport and global supply-chain networks. The research is a significant step beyond conventional input-output analysis, which does not resolve the role of individual ports, and maritime network analysis, which does not reflect the sector-specific volumes of goods transported on the network, thereby providing a misleading prioritisation of ports' criticality. Altogether, this work present a new quantitative framework that allows one to rethink the role of specific ports in the domestic and global economy, as well as the cross-border dependencies on maritime infrastructure.

We find that the approximately 50% of global trade by value is via maritime transport, although higher values are found for the Mining and Quarrying (76%) sector. Maritime trade flows are highly concentrated in a small number of ports that benefit from economies of scale and are well-integrated with the maritime and hinterland networks. Around 50 ports (out of the 1380 considered) are responsible for 50% of global maritime trade, with this trade unevenness being much larger for certain sectors such as the manufacturing of Textiles and Wearing Apparel and Transport Equipment.

Low income economies and SIDS depend disproportionally on their port infrastructure for trade. Low income countries import 1.5 times more by means of maritime transport than high-income countries, while SIDS have a twice as high maritime import dependency compared to non-SIDS. Therefore, investments in reliable port infrastructure in low income countries and SIDS are essential if further economic growth is not to be inhibited by port capacity (Limão and Venables, 2001). The benefits of increasing trade facilitation provided by ports may reach beyond the port boundaries, as ports tend to attract industry clusters (Fujita and Mori, 1996; Wang and Wang, 2019) and lower transaction costs in trade, which could lead to indirect benefits through access to international markets (e.g. food availability, expending exports markets) (Arvis *et al.*, 2016; Janssens *et al.*, 2020; Nechifor and Ferrari, 2020).

We find large cross-border dependencies between ports and the economies they serve due to land connections or transhipment services. Globally, transhipment services and the use of ports in foreign (land-connected) countries contribute to 35% of global port throughput. We identify important cross-border links between landlocked countries in Africa and South America and specific coastal ports, as well as island economies in the Pacific and the Caribbean that rely on regional transhipment hubs. The mutual dependency of economies on foreign maritime infrastructure means that there are potential spill-overs when shocks or structural changes occur to either the economy or the maritime network. For instance, strong economic growth in landlocked economies or improved cross-border transport networks between landlocked countries and its maritime neighbours (e.g. the Belt and Road Initiative and the Bioceanic Road Corridor) can lead to increasing demand at the connected ports.

Port are further found to be essential to integrate domestic and global supply-chains. In relative terms, every USD flowing through a port is associated with 4.3 USD, on average, of economic activity. While some of the world's largest ports are found to be critical for the global economy (>1.4% of global output depends on trade going through these ports), we identify a number of ports (40) in trade-dependent economies that are critical for >10% of domestic industry output. The position of ports within supply-chains depends on the relative importance of domestic versus foreign and forward versus backward supply-chain linkages. Similar ports in terms of size may be found at different ends of the spectrum, which has important implications for the feedback between the economy and trade flows through ports, and for evaluating the potential magnitude and spatial extent of supply-chains losses if ports are disrupted.

Finally, we find that for every 1000 USD increase in final demand (e.g. domestic consumption and exports) in an economy, the ports serving that economy experience a median 85 USD increase in maritime imports. However, some (27) ports import over 100 USD per 1000 USD change in final demand in the economies they serve, most of which are ports serving small island economies, but also ports serving landlocked economies (e.g. Dar Es Salaam, Djibouti). While the maritime import requirement per USD demand change is lower for low income countries than high income countries, the import sensitivity of low income countries is expected to increase as economies grow, become more diversified and better integrated in global supply-chains.

Our quantitative modelling framework paves the way for future research in various disciplines. First, our disaggregated analysis of global trade flow could allow estimating the carbon emissions embedded into maritime transportation and can help allocate these emissions to countries and sectors (Schim van der Loeff, Godar and Prakash, 2018; Liu *et al.*, 2019). Second, by incorporating various transport policies into the model, such as infrastructure investments (e.g. new transport routes), improved trade facilitation (e.g. reducing transit times at borders) or a (maritime) carbon tax, the changing allocation of freight flows could be evaluated. Third, by analysing future trade flows, the current analysis could help quantify the future investment needs in terms of new port infrastructure. Finally, by coupling this framework to a disaster impact model (Chen and Rose, 2018), the economic-wide losses (domestic and global) from port or maritime transport disruptions could be assessed, including the future losses due to climate change (e.g. sea-level rise).

In conclusion, ports are closely tied to the economy by facilitating trade flows that connect global supply-chains networks. Our research emphasises the need to rethink the key distinctive features of ports in terms of their criticality for the domestic and global economy, which are largely hidden in aggregate port-level trade statistics. We further highlight the need to integrate long-term planning of port infrastructure with a system-wide understand of the interconnected transport and the economic system. Given the large societal dependencies on maritime transport, evaluating the key links, feedbacks and dependencies between ports and the economy is imperative for the sustainable development of economies.

5.4 Methods

5.4.1 Overview

We describe the methodology of the modal split model, the maritime transport model and the link between ports and supply-chains using the MRIO tables. Throughout the analysis, we use national economies as the spatial-level of aggregation, which we further disaggregate to the port-level. This because the international trade data and global supply-chain database are constructed on a country-by-country basis, restricting using subnational economic data. We do recognise that this might bias some of the results as some interpretations of the results might be related to the size of the economy. Further, throughout this research, ports are defined as one or multiple terminals within a specified port boundary, which have been delineated in line with the World Port Index, the most widely used database of ports.

5.4.2 Modal split model

We develop a global modal split model to predict the share of maritime trade in every bilateral trade flow on a commodity level. A detailed description on the model is included in Supplementary Note A2.1. A model choice model intends to predict the allocation of freight transport flows for a given Origin-Destination (O-D) over alternative and competing transport modes (de Jong, 2013). Transporting goods between every O-D using a certain mode has a given utility that the shipper intends to maximize, which includes mode-specific variables (cost, time), O-D specific variables (income, neighbouring countries), and commodity specific variables (quantity, value to weight ratio, perishable). We fit the modal split model based on reported modal split data in international trade from UN Comtrade (United Nations Statistical Division, 2020). We use this model to predict the modal split in every bilateral trade flow reported in the harmonized BACI trade database (Gaulier and Zignago, 2010). This database contains over 8 million trade flows on a commodity level, which we aggregate to a 11 sector classification system we adopt throughout this work (see Supplementary Table A2.1). This sector classification corresponds to the 11 commodity sectors included in the EORA MRIO table, which we use later on (see Link to Input-Output Tables). This country-to-country maritime trade database is used to model the supply and demand of goods across countries globally that are consequently allocated on the maritime transport network. An external validation of the model results is included in Supplementary Note A2.2.

5.4.3 Oxford Maritime Transport model

The new global maritime transport model developed for this study (the Oxford Maritime Transport model, or OxMarTrans), combines a top-down representation of transport demand (driven by predicted maritime trade flows) with a bottom-up (asset-level) representation of the maritime and hinterland transport network. Its main purpose is to accurately allocate trade flows between countries, which we disaggregate to administrative regions within countries, on the maritime transport network, taking into consideration the likely ports and maritime routes taken based on observed sector-specific capacities between 1380 ports from empirical vessel movement data (Automatic Identification System, or AIS). A detailed model description and validation is included in Supplementary Note A2.3.

To the best of our knowledge, the OxMarTrans is the most detailed global maritime transport model available. It builds upon previously developed maritime transport flow models, either specifically for container flows (Tavasszy *et al.*, 2011; Halim, Kwakkel and Tavasszy, 2016) or multiple vessel types (Martínez, Kauppila and Castaing, 2015), that are used to allocate trade between countries on the maritime transport network. However, the OxMarTrans model makes some noticeable improvements to those earlier models. First, it simulates flows between around 3400 subnational regions globally, instead of using country centroids, which better captures how different ports facilitate trade of specific hinterlands. Second, it include a multi-model hinterland transport network, which therefore captures how the port choice is driven by the integration (better connectivity or availability of alternative modes) of ports within their respective hinterlands. Third, we embed an observed maritime transport network, based on actual vessel movements into the model, which therefore takes revealed route preferences (e.g.

strategic route decisions) into consideration. Previous work has not included this, making it hard to realistically model route choices, in particular transhipment flows. Fourth, we add sector specific constraints to the model framework, helping us to capture the specialisation of different ports and, hence, the specific cargo they handle. Fifth, we perform a flow allocation per economic sector, the output of which provides an explicit link with a MRIO, which has not be done in earlier modelling frameworks.

The model output captures, per origin and destination country and economic sector, the share of maritime trade going through specific ports, in terms of the points of exports, transhipment and imports, as well as the maritime and land-route route taken. In this way, we can analyse both the trade flows on a port-level and the use of certain transport routes (e.g. Suez and Panama canal or hinterland transport corridor) to trade goods between country pairs.

5.4.4 Link to Input-Output tables

To connect the port-level trade flows to an I-O table, we use the latest EORA MRIO (Lenzen *et al.*, 2012) (2015 at the time of writing), which describe the intercountry and interindustry supply-chain dependencies for 190 economies. Out of the 207 countries included in the port-to-port trade network, 176 countries are included in the MRIO. Trade flows included in the MRIO table are not always similar as those included in the BACI trade database (Gaulier and Zignago, 2010), and hence we can only modify overlapping trade flows for this analysis (since we only derive maritime percentages for these specific trade flows).

The import coefficient is derived in line with the work of Hummels *et al*. (Hummels, Ishii and Yi, 2001), that used the concept of import coefficients to quantify the amount of imports embedded in the export of a country (i.e. vertical specialisation). Although the methodology of Hummels *et al*. (Hummels, Ishii and Yi, 2001) was developed for a single country I-O table, Dietzenbacher showed that the same result holds for a MRIO (Dietzenbacher, 2010). Our port-level import coefficient (PLIC) metric quantifies the amount of imports through a port (*p*) that serve as a country (*k*) that are embedded in exports (***e*,** vector of exports) and domestic final consumption (***c***, vector of consumption). In a MRIO table, the input coefficients matrix (***A***) for country is derived from its interindustry trade (***Z***) and industry output (***x***). For a country k = 1, this consists of $\boldsymbol{A}^{11} = \boldsymbol{Z}^{11}(\hat{x})^{-1}$ for domestically produced inputs and $\boldsymbol{A}^{k1} = \boldsymbol{Z}^{k1}(\hat{x})^{-1}$ for inputs imported from country *k (k ≠1)*.

The domestic output necessary for $\boldsymbol{e}$ is $(\boldsymbol{I}-\boldsymbol{A}^{11})^{-1}\boldsymbol{e}$ and for $\boldsymbol{c}$ is $(\boldsymbol{I}-\boldsymbol{A}^{11})^{-1}\boldsymbol{c}$, which require imports $\boldsymbol{M} = \sum_{c=2}^{k} \mathbf{A}^{c1}$(c = 2 to k means input from other countries). Hence, the total imports to meet $\boldsymbol{e}$ is $\boldsymbol{s}'\boldsymbol{M}(\boldsymbol{I}-\boldsymbol{A}^{11})^{-1}\boldsymbol{e}$ and to meet $\boldsymbol{c}$ is $\boldsymbol{s}'\boldsymbol{M}(\boldsymbol{I}-\boldsymbol{A}^{11})^{-1}\boldsymbol{c}$, with $\boldsymbol{s}$ a summation vector. To find imported goods going through a port, we modify the ***M*** matrix using the port-to-port trade network, by first making ***M*** = *0*, and filling the ***M*** matrix with the fraction of country-to-country trade (share time trade flow) that goes through a port per sector (*s*) (with $\boldsymbol{A}_p^{c1}$ the port-level imports from country *c* to country 1 to port *p*). This results in a new $\boldsymbol{M}_p$ per port that covers the input coefficients from country *k* to the host country of the port (country *c = 1*), which are being transported through this port. Using this, we can find the PLIC metrics by

$$PLIC_{dom,p,c} = \frac{\boldsymbol{s}'\boldsymbol{M}_{\boldsymbol{p}}\left(\boldsymbol{I}-\boldsymbol{A}_p{}^{11}\right)^{-1}\boldsymbol{c}_{\boldsymbol{c}}}{\boldsymbol{s}'\boldsymbol{c}_{\boldsymbol{c}}}$$

and

$$PLIC_{exp,p,c} = \frac{\boldsymbol{s'M_p}\left(\boldsymbol{I} - \boldsymbol{A}_p{}^{11}\right)^{-1}\boldsymbol{e_c}}{\boldsymbol{s'e_c}}$$

describing the port-level imports required to meet the final demand for the economies that a specific port serves ($PLIC_p = PLIC_{dom,p} + PLIC_{exp,p}$). The total import multiplier for a country (CLIC) is found by aggregating the PLIC-measures per port that serve the demand of a country (*p,c*) ($CLIC = \sum PLIC_{p,c}$). The sector-specific import multipliers on a country-level are found by replacing $\boldsymbol{c}$ and $\boldsymbol{e}$ with a vector with a one for the specific sector and a zero otherwise.

The port-level output coefficient (PLOC) metric is a variation of the Hypothetical Extraction Method (HEM) (Schultz, 1977; Temurshoev and Oosterhaven, 2014; Dietzenbacher, van Burken and Kondo, 2019) used in I-O analysis, in which a sector is hypothetically set to zero (the i-th row and j-th column of matrix $\boldsymbol{A}$) in order to evaluate the interindustry dependencies and importance for the economy through changes in the industry output. For the PLOC, we quantify the output changes to the economy by removing the trade flows going through a port from the I-O table. To do this, we use both supply-driven (Ghosh) and demand-driven (Leontief) versions of the I-O table to find the forward (supply-driven) and backward (demand-driven) linkages. Using a Ghoshian model is justified here as we look at reductions in industry output (see Rose and Wei for a discussion (Rose and Wei, 2013)). The PLOC metric is derived by (1) modifying the interindustry trade matrix ($\boldsymbol{Z}$) and (2) the final demand matrix ($\boldsymbol{y}$) to account for the trade flows going through a port. First, we remove the port-level trade flows (imports, exports and transhipments) from $\boldsymbol{Z}$ and re-evaluate the new $\boldsymbol{A}_{p,1}$ using the demand-driven model and the new $\boldsymbol{B}_{p,1}$ using the supply-driven model ($\boldsymbol{B}_{p,1} = \widehat{\boldsymbol{x}^{-1}}\,\boldsymbol{Z}$). We find the backward losses in industry output ($\Delta \boldsymbol{x}_{p,1,ind,b}$) by re-calculating industry output ($\boldsymbol{x}_{p,1,ind}$) with the modified direct requirement matrix:

$$\Delta \boldsymbol{x}_{p,1,ind,b} = \boldsymbol{x} - \left(\boldsymbol{I} - \boldsymbol{A}_{p,1}\right)^{-1} \boldsymbol{y}$$

And the new industry output for the forward linkages ($\Delta \boldsymbol{x}_{p,1,ind,f}$):

$$\Delta \boldsymbol{x}_{p,1,ind,f} = \boldsymbol{x} - \boldsymbol{v}\left(\boldsymbol{I} - \boldsymbol{B}_{p,1}\right)^{-1}$$

with $\boldsymbol{v}$ the vector of value-added. The changes in industry output is the addition of the changes in domestic output ($\Delta \boldsymbol{x}_{dom,ind,b}$; $\Delta \boldsymbol{x}_{dom,ind,f}$) and change in output on the rest of the economy ($\Delta \boldsymbol{x}_{row,ind,b}$; $\Delta \boldsymbol{x}_{row,ind,f}$). Moreover, we evaluate the changes in industry output due to the port-level trade embedded in direct consumption. This is done by modifying the demand matrix ($\boldsymbol{y}$) with the equivalent reduction in domestic final consumption (imports) and the reduction in final consumption in other countries (exports). Output losses associated with changes in final consumption in a port in country 1 ($\boldsymbol{y}_{p,1}$) can be found by solving:

$$\Delta \boldsymbol{x}_{p,1,con,b} = \boldsymbol{x} - (\boldsymbol{I} - \boldsymbol{A})^{-1}\left(\mathbf{y} - \mathbf{y}_{\mathbf{p},\mathbf{1}}\right)$$

From $\Delta \boldsymbol{x}_{p,1,con,b}$ we can find changes in domestic output ($\Delta \boldsymbol{x}_{dom,con,b}$) and changes in output for the rest of the economy ($\Delta \boldsymbol{x}_{row,con,b}$) in a similar fashion as described above. The forward losses associated with trade in final consumption are simply the trade flows of final consumption, with imports leading to a reduction of domestic consumption ($\Delta \boldsymbol{c}_{dom,con,f}$) and exports leading to a reduction in foreign consumption ($\Delta \boldsymbol{c}_{row,con,f}$).

This yields the PLOCA metric, which can be derived from changes in output and consumption:

$$PLOCA = (\Delta \boldsymbol{x}_{dom,ind,b} + \Delta \boldsymbol{x}_{dom,con,b}) + (\Delta \boldsymbol{x}_{dom,con,f} + \Delta \boldsymbol{x}_{dom,ind,f}) + (\Delta \boldsymbol{x}_{row,ind,b} + \Delta \boldsymbol{x}_{row,con,b}) + (\Delta \boldsymbol{c}_{row,con,f} + \Delta \boldsymbol{c}_{row,ind,f})$$

from which PLOCR can be derived:

$$PLOCR = \frac{PLOCA}{T}$$

With $\boldsymbol{T}$ the throughput going through the port. The relative importance of the global versus domestic economic linkages and forward versus backward economic linkages are derived by dividing the different components of PLOCA (neglecting the final consumption changes). The global and domestic importance of ports is simply derived by dividing the total industry output changes with the global and domestic industry output. A similar exercise is done for the final consumption changes.

6 Multi-hazard risk to global port infrastructure and resulting trade and logistics losses

Chapter 6 introduces a multi-hazard risk analysis framework that quantifies the present-day physical asset damages to port and critical (i.e. road, rail, electricity) infrastructure, and the trade and logistics losses as a result of port downtime.

Paper: Verschuur, Koks, Li and Hall, Multi-hazard risk to global port infrastructure and resulting trade and logistics losses, *under review in Communications Earth and Environment*

Contributions: Jasper Verschuur: Conceptualization, Methodology, Formal analysis, Writing – Original Draft, Writing – Review & Editing, Visualization. **Sihan Li**: Resources, Writing – Review & Editing. **Elco Koks**: Conceptualization, Writing – Review and Editing, Supervision. **Jim Hall:** Conceptualization, Writing – Review and Editing, Supervision

Data and code availability: The port database, risk output and code for analysis will all be published upon acceptance of this paper. All additional materials and codes, except the pluvial and fluvial hazard maps (which are licensed), can be requested from the corresponding author upon reasonable request.

Abstract:. Despite their economic importance, the risk that ports face from multiple natural hazards has not yet been monetised on a global scale. Here, we perform an asset-level risk analysis of global port infrastructure from multiple hazards, quantifying the risk to physical asset damages and logistics services (i.e. port-specific risk), and risk to maritime trade flows (i.e. trade risk). We find that the vast majority of ports (~86%) are exposed to more than three hazards. Globally, port-specific risk totals 7.5 USD bn per year, dominated by tropical cyclone impacts (~32%). In addition, 63.1 USD bn of trade is at risk every year, with trade risk as a fraction of total trade being particularly high in Small Island Developing States. Our result underline that port resilience is determined by various critical factors (e.g. engineering standards, operational thresholds, recovery duration) that vary widely across ports, requiring tailored solutions to improve port resilience.

6.1 Introduction

Ports are essential for the well-functioning of economies and global supply-chains (Becker *et al.*, 2013; Rose and Wei, 2013; Verschuur, Koks and Hall, 2022). However, their strategic location along rivers and low-lying coastal areas makes them exposed to the impacts of climate extremes and natural disasters (e.g. extreme waves, cyclones, earthquakes). For instance, Hurricane Ike (2008) caused an estimated 2.4 USD billion worth of damages to ports in Texas (FEMA, 2008), whereas the 2013-2014 floods in the

United Kingdom damaged port infrastructure worth 1.8 GBP million (Chatterton *et al.*, 2016). The impacts of port disruptions are often felt beyond the port boundaries, as port closures can result in wider economic losses through maritime transport and global supply-chain networks that depend on ports' trade facilitation function (Rose and Wei, 2013; Levermann, 2014; Verschuur, Koks and Hall, 2022). Given their economic importance and the large sums of money invested in port construction and operations from the private sector (around 92 USD billion since 1990 in low and middle income countries alone) (World Bank, 2021), combined with the expected increase in natural hazard risk due to climate change (Allen, McLeod and Hutt, 2021; Izaguirre *et al.*, 2021) and the predicted near tripling of maritime trade by 2050 (ITF, 2019), detailed risk information at a global scale is essential to guide port infrastructure planning and investments, and manage supply-chain risks.

Since ports form nodes in global networks of maritime supply chains, it is essential to take a global perspective to accurately estimate the risks from catastrophic port disruptions. However, the academic literature so far has inadequately addressed this. On the one hand, previous large-scale (continent or global) analyses have mainly looked at the exposure of ports, with ports represented as single points, to coastal flooding (Christodoulou, Christidis and Demirel, 2019) or multiple operational thresholds from climate extremes (Izaguirre *et al.*, 2021). Although useful for analysing the frequency of occurrence of a single or multiple hazards, these studies fail to monetise the economic damages to physical assets, since asset locations (e.g. terminals, road, rail) are not included, nor the associated disruption pathways of port downtime and the losses associated with that (e.g. loss to trade, revenue, delays). On the other hand, a number of detailed (asset-level) port risk analysis, that include the different ways in which a port may be disrupted, have been performed, but only on a local scale covering one or a small subset of ports (Aerts *et al.*, 2018; Abdelhafez, Ellingwood and Mahmoud, 2021; Allen, McLeod and Hutt, 2021).

Despite the amount of work that has been done, we identified several remaining challenges to scale up detailed risk analysis to a global scale. First, ports can be damaged or disrupted by several different hazards which impact upon the port's physical infrastructure and operations in different ways, making risk analysis complex. Apart from impacts to the port assets themselves (e.g. cranes, terminals), ports are embedded in local critical infrastructure networks (e.g. rail, road, electricity), damages to which can halt port operations even if the port itself is not damaged. In fact, hazard impacts to critical land-side infrastructure is identified as a key bottleneck for various ports, both in the developing and developed world (Stenek *et al.*, 2011; Canevari *et al.*, 2015; Aerts *et al.*, 2018; Allen, McLeod and Hutt, 2021). Incorporating this local complexity into a global analysis requires a large amount of local port-specific data as well as analysis of a variety of port-specific hazards and failure mechanisms. So far, this has been impossible given that (1) no global port asset database exist, (2) most studies ignore the link between port operations and the critical infrastructure networks they depend on, and (3) global hazard datasets often have low resolution, making them incompatible with asset-level risk analysis, or requires additional local information (e.g. presence of a breakwater, depth of approach channel) to adequately capture the port's operational thresholds. Second, disruptions to trade flows going through ports can lead to additional logistics losses due to transportation delays and downtime, which can incur costs to those involved in facilitating logistics services (e.g. port operators, carriers and shippers) (Zhang and Lam, 2015; Y. Zhang *et al.*, 2020). These losses could be substantial, as illustrated by the 2021

Suez blockage (LaRocco, 2021), and could exceed physical asset damages. In order to quantify such additional trade and logistics losses, detailed information on port-level trade flows is needed, which is not yet readily available on a global scale. Hence, studies looking at logistics losses have only quantified the scale of these losses for the handful of ports for which such information is available (Y. Zhang *et al.*, 2020).

To bridge these gaps, this study presents the first asset-level risk analysis for 1380 ports globally, considering multiple hazards and failure mechanisms. We quantify both the physical damages to infrastructure assets as well as the associated logistics and trade losses due to port downtime (either due to asset reconstruction or operational downtime). To do this, we create a new port infrastructure and land-use database that contains all the essential port infrastructure assets (terminals, breakwaters, cranes), critical infrastructure assets (road, rail, electricity transmission, power generation), and industrial facilities within the immediate port area (defined as the 1km buffer around the port terminals). Our risk framework includes both operational disruptions to ports (that do not cause damage), which typically occur due to extreme wind, temperature, wave heights and overtopping, as well as the physical damages to port infrastructure as a result of multiple natural hazards, specifically tropical cyclones, earthquakes, river flooding, pluvial flooding and coastal flooding. Using a failure tree methodology, we capture how multiple failure pathways can result in impacts to the port's operational status. Moreover, by combining our risk estimates with a recently developed port-level trade network (Verschuur, Koks and Hall, 2022) (Chapter 5), which was constructed from a big dataset of vessel Automatic Identification System (AIS) observations (Verschuur, Koks and Hall, 2021a), we estimate the amount of trade disrupted (trade at risk) and the additional logistics losses to port operators (revenue losses), carriers (losses of late delivery) and shippers (inventory costs and value of time) (Methods).

To investigate the factors that drive the calculated risk estimates, and to account for the many uncertainties associated with such a global analysis, we perform a large-scale sensitivity analysis that covers, among others, the uncertainties associated with the resilience of ports. Port resilience, which reflect the ability to prevent, cope and recovery from external disturbances (Linkov *et al.*, 2014), is incorporated in our framework by varying the engineering design standards (e.g. susceptibility of port infrastructure to damage during extreme conditions), reconstruction costs of port and critical infrastructure assets (which can vary significantly across ports), and the measures in place to improve operability during extreme conditions (e.g. pilot vessels and tug boats that can cope with larger wave heights) or shorten the recovery time after disruptions (e.g. business continuity plans). As well as providing an uncertainty range associated with our risk estimates, the sensitivity analysis thus provides insights into how various ports can benefit from further investments or operational adaptations to improve resilience, or, on the other hand, how a decline of resilience in the future will worsen the risk of port failures.

Altogether, the analysis presented in this work is the first comprehensive overview of natural hazard risk to ports on a global scale, providing essential insights for policy-makers, private-sector investors, insurance companies and other maritime stakeholders. It further sets the scene for analysing changes in risk due climate change and the need for port expansions, as well as performing adaptation analysis.

6.2 Results

The multi-hazard risk framework includes both the extremes that most disrupt port operations (extreme wind, temperature, waves and overtopping), hereafter referred to as marine extremes, and the natural hazards that can cause physical failure of the port infrastructure (cyclone wind, earthquakes, river flooding, pluvial flooding and coastal flooding). We adopt two risk metrics throughout: the port-specific risk and the trade risk, both measured in monetary value.

Port-specific risk is the sum of three types of impacts incurred by the actors who own, operate and use ports: (1) the physical damages to port infrastructure (e.g. terminals, cranes, industrial facilities), (2) the physical damages to critical infrastructure in the port vicinity (electricity, road, rail and power plants) upon-which the port depends, and (3) the additional logistics losses to port operators, carriers and shippers as a result of downtime due to the exceedance of operational thresholds or asset reconstruction (see Methods). Although port infrastructure is considered a critical infrastructure in itself, in this study we refer to critical infrastructure as the dependent critical infrastructure to support the efficient functioning of the port, including road, rail, and electricity generation and transmission infrastructure.

Disruptions to trade flows can have widespread economic impacts, by impacting supply chains within or across borders that are essential for the production and consumption of goods (Rose and Wei, 2013; Koks and Thissen, 2016; Rose, Wei and Paul, 2018). The likelihood of such trade bottlenecks is related to the frequency and duration of port downtime and the flow of goods through ports that is potentially disrupted. Therefore, we define trade risk in this paper as the amount of trade (measured in monetary value) that is expected to be disrupted by natural hazards and marine extremes on an annual basis (see Methods).

Throughout this paper, for both port-specific risk and trade risk, we report the median risk estimates and the confidence interval (CI: 5 to 95th percentile) as found by performing the sensitivity analysis (see Methods).

6.2.1 Multi-hazard exposure

Most ports are exposed to damages and disruptions from a multitude of extremes and natural hazards. 40.1% (22.1 - 63.1%) of the 1380 ports are exposed to extreme maritime conditions that surpass the operational thresholds. The vast majority of ports (94.8%) are exposed to more than one natural hazard, with 50% of ports being exposed to four or five natural hazards. Fluvial and pluvial flood hazards are most prevalent with 80.4% (70.9 – 81.4%) and 84.3% (57.8 - 88.2%), of ports, respectively, being exposed to these natural hazards. Some of the hotspots of multi-hazard exposure are in Japan, the West Coast of the United States and Middle-America, New Zealand, Taiwan and parts of mainland China (Supplementary Figure A3.1a). Ports in South America, parts of Northern, Western and Eastern Africa, and Northern and Eastern Europe are only exposed to two or less hazards (Supplementary Figure A3.1b). Hence, the vast majority of ports need to consider multiple hazards in the design and operations of infrastructure. For instance, the foundations of quay walls need careful consideration when exposed to earthquakes, the orientation and design of breakwaters when exposed to extreme waves and surges, and the drainage system when exposed to fluvial and pluvial flooding.

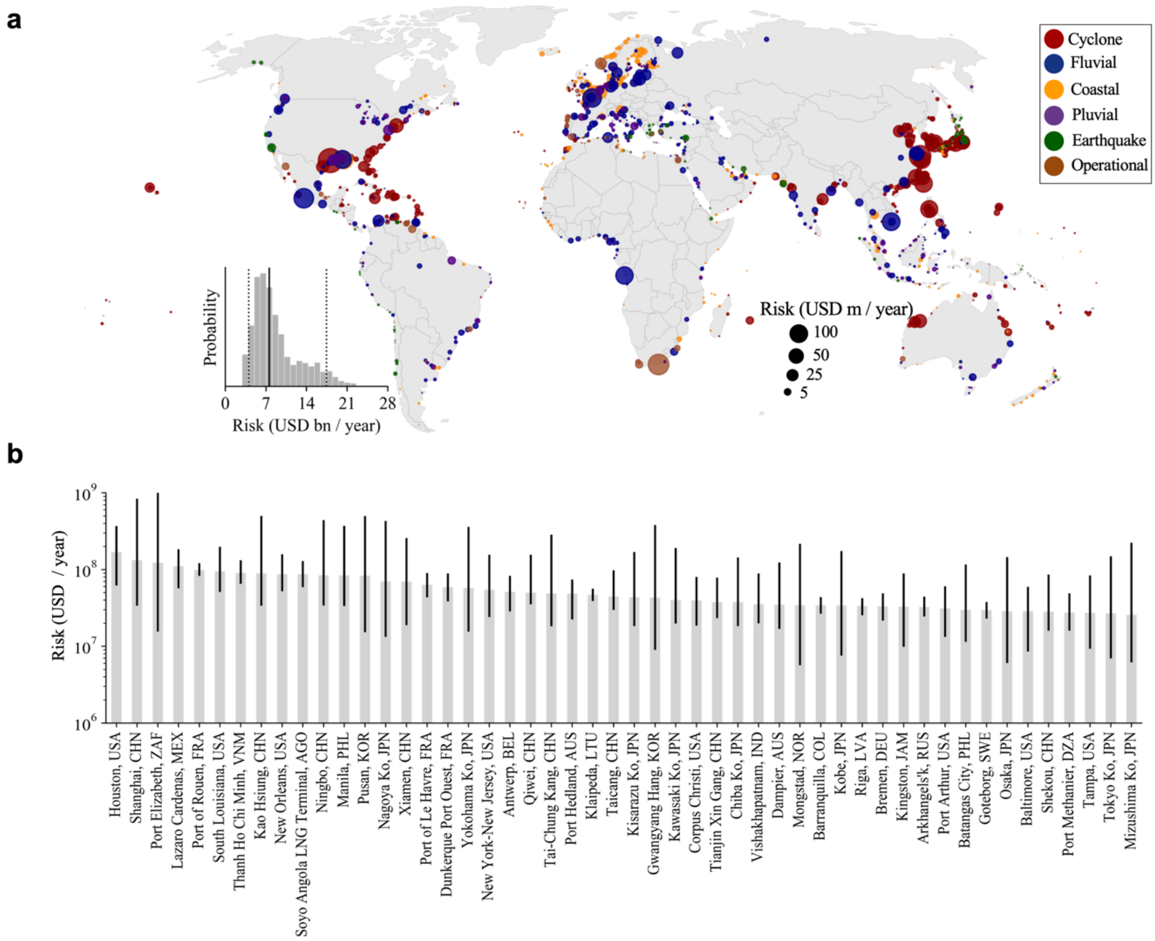

Figure 6.1: Global footprint of port-specific risk. (a) The median risk per port, expressed in USD m per year, with the colour indicating the dominant hazard. The histogram illustrates the globally aggregated risk across the 10,000 samples with the black line indicating the median and the dashed lines indicating the 5th and 95th percentiles. (b) The top-50 ports in terms of median expected risk (bars). The errors bars reflect the 5-95th percentile of the risk estimates based on the 10,000 samples. Note the logarithmic y-scale.

6.2.2 Spatial footprint of port-specific risk

Figure 6.1a shows the expected port-specific risk and the dominant hazard (colour of dot), while Supplementary Figure A3.2a-f show the port-specific risk estimates per hazard. On a global scale, the median port-specific risk is found to be 7.6 (4.0 - 17.4) USD bn per year (histogram Figure 6.1a). The largest port-specific risk is attributed to tropical cyclones (TCs) with a median risk of 2.4 (0.7 – 12.2) USD bn per year, followed by fluvial flooding 1.9 (0.7 – 12.2) USD bn per year, coastal flooding 0.8 (0.5 – 1.23) USD bn per year, pluvial flooding 0.7 (0.2 – 1.6) USD bn per year, operational exceedances 0.5 (0.06 – 2.4) USD bn per year, and earthquakes 0.2 (0.1 – 1.3) USD bn per year. The relative importance of the different hazards on a port level, however, varies geographically (colour dots in Figure 6.1a). TC is the leading hazard globally (for 25.2% of ports), in particular for the Caribbean, Eastern Asia and Northern Australia, whereas fluvial (22.6%) and coastal flood (23.7%) are the leading hazards for Western and Northern Europe. The spatial footprint of port-specific risk contributed by flooding are driven by the location of rivers and occurrence of extreme coastal water levels on the one hand, and the local presence of flood protection standards, or lack thereof, and the freeboard of the terminals on the other hand. Although earthquake-induced risk is small overall, earthquakes are still the leading hazard for 10.8% of the ports, with hotpots found in Chile, parts of the Mediterranean and Northern Japan. In some countries, such as India, United States and Australia, different dominant hazards are identified across the country, emphasising that port-specific risk is determined by the local conditions and, as such, it is essential to perform local risk analysis that take the multiple hazards into consideration in a unified risk framework.

Figure 6.1b shows the top 50 most at risk ports globally in terms of expected port-specific risk. The largest port-specific risk is found for ports in Asia, in particular mainland China and Taiwan (China), ports in the Gulf of Mexico, and ports in Western Europe. The ports of Houston (United States, 169.0 million USD m per year), Shanghai (mainland China, 133.2 USD m per year), Port Elizabeth (South Africa, 123.4 USD m per year), Lazaro Cardenas (Mexico, 110.9 USD m per year) and Rouen (France, 98.7 USD m per year) are found to be the top five most at risk ports. The port of Houston faces the largest risk from a combination of cyclone wind, pluvial flooding and fluvial flooding, whereas for the port of Shanghai cyclone wind is by far the most important hazard. Fluvial flooding is the dominant hazard for the ports of Rouen and Lazaro Cardenas, while the exceedance of operational thresholds, in particular from extreme wave heights, contributes most to the port-specific risk for Port Elizabeth. Around half the ports globally face risk larger than 1 USD m per year, with 160 ports facing moderately high risk (10 USD m per year) and 21 ports facing very high risk (>50 USD m per year). Most of the top 50 ports are very large ports in terms of estimated freight flows (>10 USD bn annually), therefore having large port areas and value of logistics services exposed.

To put this number into perspective, the port-specific risk is expressed in terms of the risk per square metre of port area (referred to as relative risk hereafter), and grouped according to the income level of the country (following the 2021 World Bank Income Classification). Ports in high income countries face a relative risk of 123.4 (55.7 - 379.5) USD per year per m^2, which is slightly higher than ports in low income countries (117.7, 45.7 – 312.1) USD per year per m^2 and upper middle income countries (118.4, 53.3 – 404.7) USD per year per m^2, but lower than ports in lower middle income countries (155.5, 87.4 – 377.6) USD per year per m^2. Therefore, despite the absolute risk being particularly large in high-income countries, ports in high-income countries have the financial resources to take protective measures (e.g. higher flood protection standards, elevate terminals) to reduce risk in relative terms, compared to lower (and) middle income countries. A similar observation was made for the physical asset risk to global road and rail infrastructures (Koks *et al.*, 2019).

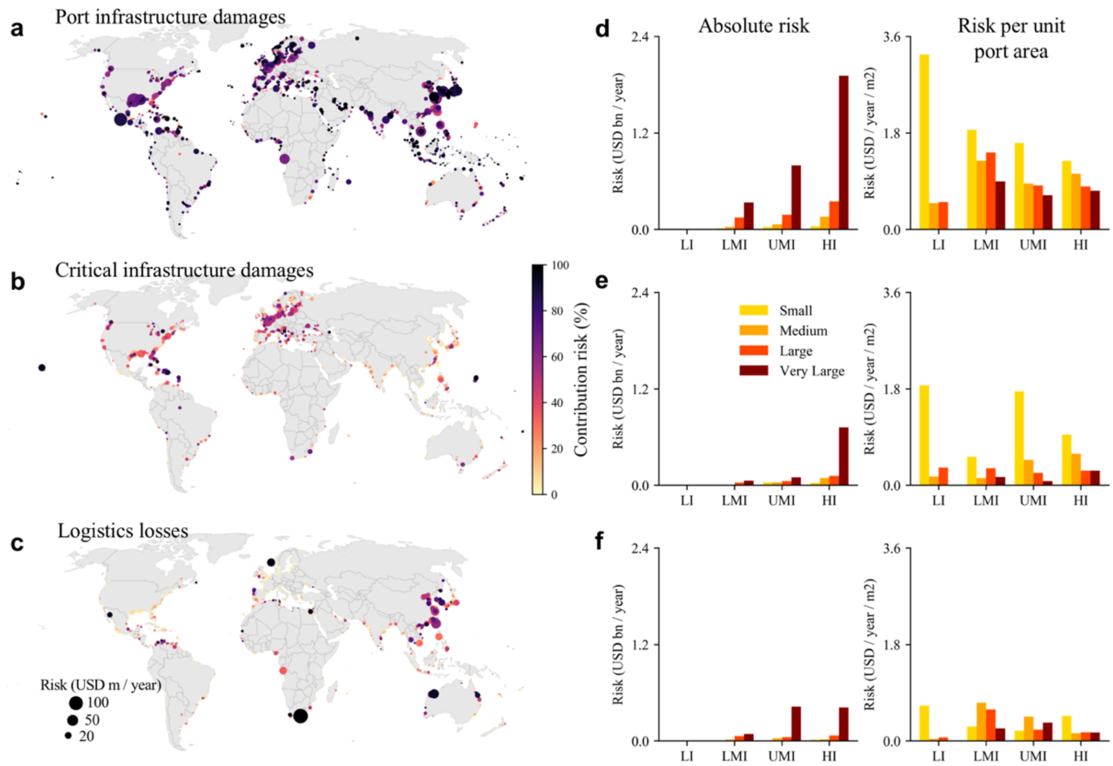

Figure 6.2: Contribution of different hazards to expected port-specific risk. (a) The contribution to the risk due to physical damages to port infrastructure. The colour indicates the fraction of contribution whereas the size of the marker denotes the risk. (b) Same as (a) but for physical damages to critical infrastructure. (c) Same as (a) but for the logistics losses. (d) On the left, the absolute risk due to the physical damages to port infrastructure, grouped by the size of the port (based on four quantiles of the total port area mapped) and the level of income of the country (based on the World Bank Income Classification), is shown. On the right, the relative risk (per square metre of port area) is shown. (e) Same as (d) but for physical damages to critical infrastructure. (f) Same as (d) but for the logistics losses. All values reflect the median estimate across the 10,000 samples.

6.2.3 Contribution risk factors to port-specific risk

The three different risk factors (port infrastructure damages, critical infrastructure damages, logistics losses) contribute to the port-specific risk to various extents. Physical damages to port infrastructure are responsible for 58.6% of the port-specific risk to ports globally, followed by logistics losses (22.2%) and critical infrastructure damages (19.2%) (Supplementary Figure A3.3).

Tropical cyclone wind, causing frequent downtime to ports (Verschuur, Koks and Hall, 2020) (Chapter 3), is the hazard that causes most logistics losses. Of the cyclone-induced risk, 30% are logistics losses, while for the other natural hazards, logistics losses are small relative to port infrastructure and critical infrastructure damages (ranging from 1.2% for earthquakes to 8% for fluvial flooding). In contrast, coastal, pluvial and fluvial flooding all account for relatively large critical infrastructure asset damages, contributing 28.2%, 24.5% and 22.8%, respectively, to port-specific risk globally (Supplementary Figure A3.3).

Figure 6.2a-c illustrate the relative importance of the three risk contributors per port, showing how the damages to port infrastructure dominates the port-specific risk. Still, risk to critical infrastructure assets is the largest contributor to port-specific risk for ~12% of the ports globally, particularly located in Europe and the United States. This result resonates with previous work (Canevari *et al.*, 2015; Aerts *et al.*, 2018; Allen, McLeod and Hutt, 2021) illustrating that critical infrastructures in the vicinity of ports are essential to consider in risk analysis and adaptation strategies, as they are often more exposed to fluvial and coastal flooding (given that port terminals are often built to higher elevations hence less vulnerable in comparison). Logistics losses are large for ports with large throughput quantities that are exposed to marine extremes and tropical cyclones, both resulting in large disruptions if ports have to shut down without major damages to infrastructure assets. Examples are Port Hedland and Port Walcott in Australia, Saldanha Bay and Port Elizabeth in South Africa, and Ulsan and Inchon in South Korea (all >70% of total).

Figure 6.2d-f show the absolute and relative port-specific risk (risk per unit port area) broken down by the size of ports (four quantiles based on the port area –

small/medium/large/very large as shown in Figure 6.2d-f) and income groups. For the port infrastructure, although the absolute risk is largest for the very large ports in high income countries, the relative risk is highest for small ports in low income countries. The high absolute port-specific risk in high income countries is in line with the expectation that more developed countries trade more and need larger port areas to facilitate the trade flow, leading to a larger number of assets at risk. In general, however, larger ports face a lower relative risk, although the differences are small across income groups and port sizes. The decrease in relative risk with income groups can be explained by the difference in exposure, but more likely due to the fact that higher income countries have the financial resources to invest more in flood protection (both river and coastal) or elevating their port terminals. For critical infrastructure, the larger ports in high income countries face the largest absolute port-specific risk, whereas, the small ports in both low income and upper middle income countries face a high relative risk (Figure 6.2e). The absolute port-specific risk is almost negligible for small ports, especially in low-income countries, with tertiary or secondary roads providing transport connectivity, which have lower replacement costs. However, small ports have higher relative critical infrastructure risk as they often only have one or two main transport or electricity infrastructure networks connecting to the port, making them more vulnerable if these assets are hazard-prone. Contrary to the above, the absolute port-specific risk as a result of logistic losses (Figure 6.2f) are largest in very large ports in upper middle income countries. The relative risk is less related to the size of the port, with both large and small ports across the income groups being faced with almost equal relative risk.

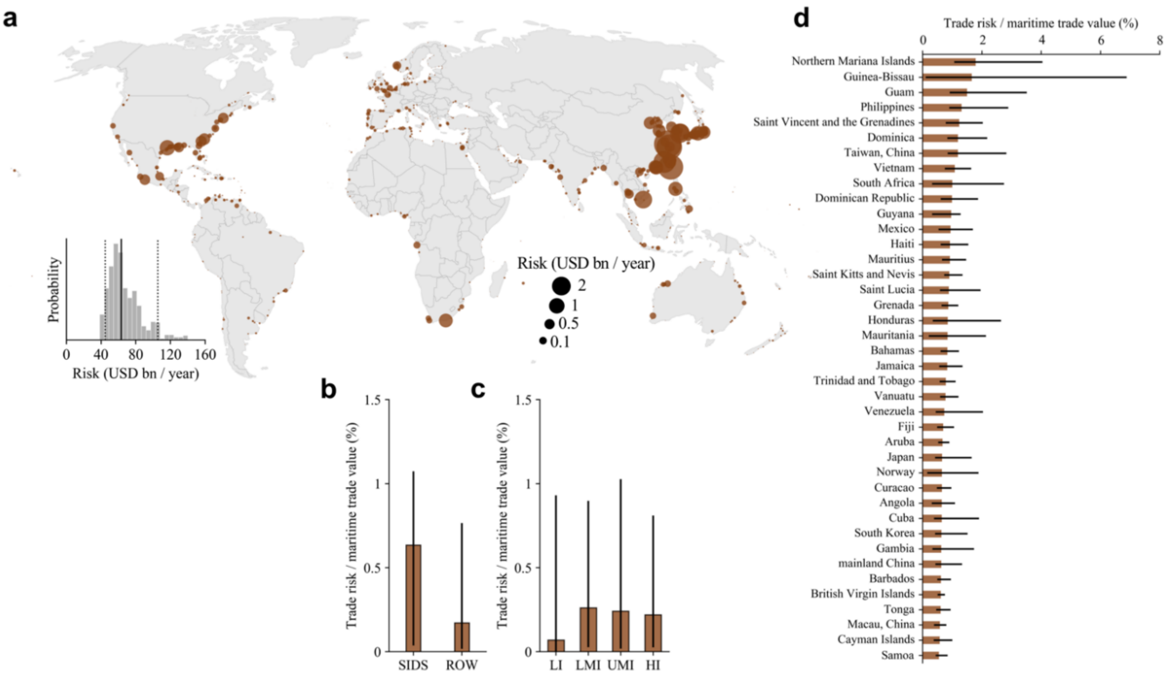

Figure 6.3: Global footprint of trade risk. (a) The median trade risk in USD bn per year, reflecting the risk to trade disruptions as a result of downtime per port. The histogram illustrates the global aggregated trade risk across the 10,000 samples with the black line indicating the median and the dashed lines indicating the 5th and 95th percentiles. (b) The distribution of the trade risk over Small Island Developing States (SIDS) and Rest of World (ROW) countries, with the bar showing the median across countries and the error bar the 5 to 95th percentiles. (c) Same as (b) but for countries grouped by the different income groups. (d) The trade risk expressed as percentage of the annual maritime trade value. The top-40 economies are depicted with the error bar indicating the 5-95th uncertainty range across the 10,000 samples.

6.2.4 Spatial distribution of trade risk

Figure 6.3a shows the global distribution of trade risk (measured in monetary value) for all the ports. On a global scale, the trade risk is estimated to be 66.9 (47.1 – 109.7) USD bn per year (histogram Figure 6.3a). In other words, around 0.80% (0.53 – 1.76%) of the total maritime trade value is at risk every year of being disrupted due to natural hazards. Locations of high trade risk are concentrated in the cyclone-prone areas of East Asia, where hazard-induced port downtime disrupts large trade flows. A total of 27 ports are associated with a trade risk of >0.5 USD bn per year with the ports of Shanghai (mainland

China), Ningbo (mainland China), Kaohsiung (Taiwan, China), Xiamen (mainland China), and Busan (South-Korea) having the highest trade risk globally.

On an aggregated level (e.g. country, economic entity), the trade risk denotes the total amount of trade measured in monetary value that could be disrupted on an annual basis. Small Island Developing States (SIDS), whose economies are critically dependent on maritime transport (Verschuur, Koks and Hall, 2022) (Chapter 5), face disproportionally high trade risk, which is 3.7 times higher than non-SIDS economies (Rest of World, ROW, in Figure 6.3b) on average (averaged across economic entities). In line with the port-specific risk estimates, lower middle income countries are found to be faced with the largest trade risk on average, while trade risk is small for low income counties (Figure 6.3c). The Northern Mariana Islands (1.8%, 1.1 - 4.0%), Guinea-Bissau (1.7%, 0.1 – 6.9%), Guam (median 1.5%, 5-95th CI: 0.9 – 3.5%), Philippines (1.3%, 0.9 – 2.9%), Saint Vincent and the Grenadines (1.2%, 0.8 – 2.0%), and Dominica (1.2%, 0.9 – 2.2%) face the largest risk of trade bottlenecks, due to the large concentration of trade through at risk ports (top 30 economies shown in Figure 6.3d).

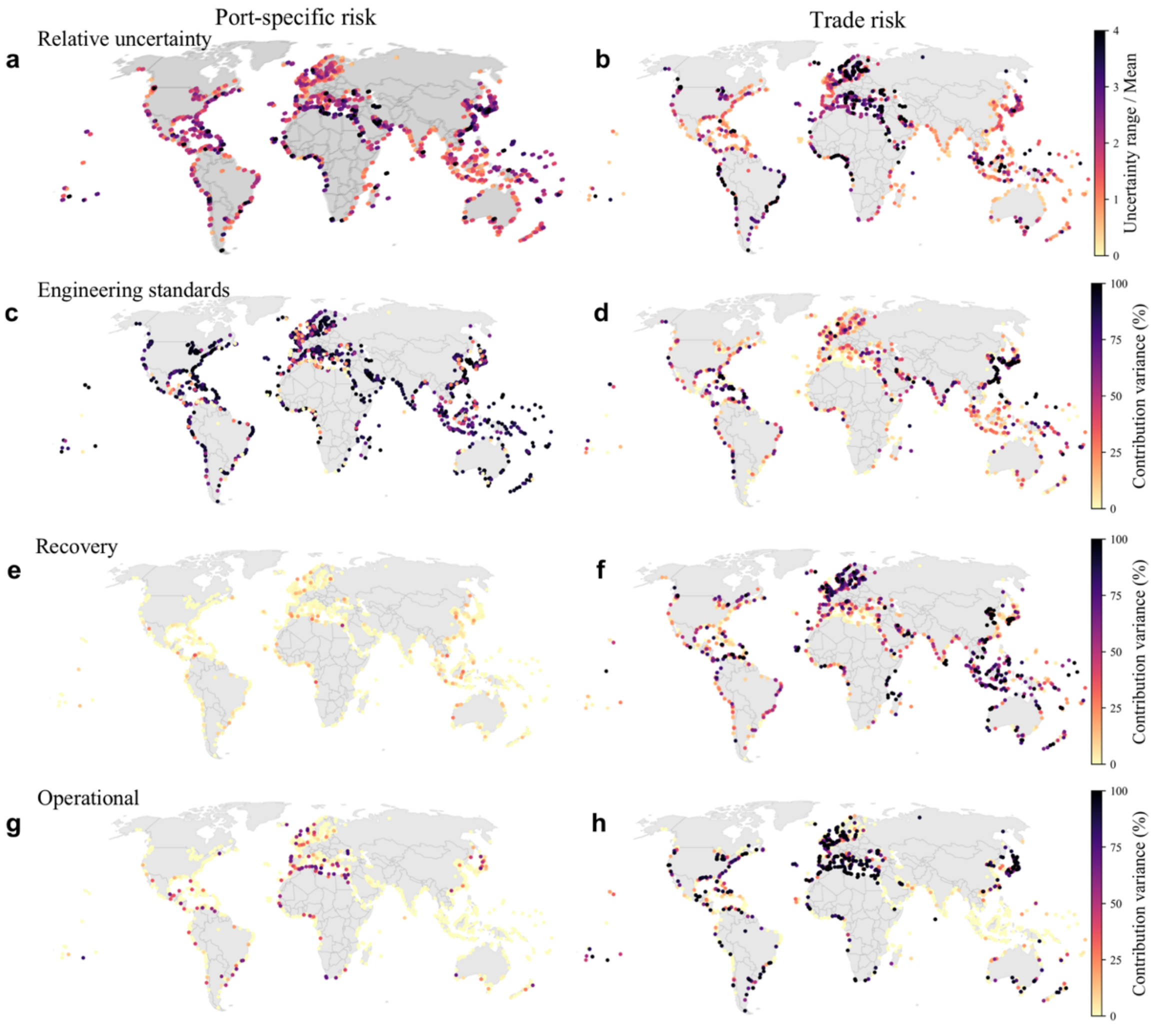

Figure 6.4: Uncertainty range and sensitivity analysis of resilience parameters. (a) The relative uncertainty, expressed as the 5-95th uncertainty range over the mean, over the 10,000 model realization for the port-specific risk. (b) Same as (a) but for trade risk. (c) The contribution of the input parameters reflecting the uncertainty in the engineering standards of ports with respect to hazard impacts (depth-damage curves) to the port-specific risk model variance. (d) Same as (c) but for trade risk. (e) The contribution of the input parameters reflecting the uncertainty in the recovery ability of ports with respect to hazard impacts (recovery curve, maximum recovery duration) to the port-specific risk model variance. (f) Same as (e) but for trade risk. (g) The contribution of the input parameters reflecting the uncertainty in the operability of ports with respect to climate extremes (wave height, wind, temperature and overtopping) to the port-specific risk model variance. (h) Same as (g) but for trade risk.

6.2.5 Sensitivity Analysis

Uncertainties are prevalent throughout the analysis and are investigated through a variance-based sensitivity analysis (see Methods). This allows us to explore the main parameters driving the variance in port-specific risk and trade risk estimates. Moreover, it elucidates the uncertainty in the risk estimates on a port-level, as these sensitivities are not uniform across the ports. Figure 6.4a illustrates the relative uncertainty estimates of the port-specific risk (expressed as the 5-95th uncertainty range over the mean value), showing that large relative uncertainties are prevalent in Africa, the Middle-East and East Asia. This difference in the uncertainties illustrates that part of the port-specific risk is unavoidable, or insensitive to parameter input, whereas part of the port-specific risk is associated with the sensitivity of some key parameters, especially those reflecting the current level of resilience of the ports. Figure 6.4b also shows the relative uncertainty estimates for the trade risk estimates, which are overall higher than the port-specific risk and have a different spatial pattern. For trade risk, large relative uncertainties are identified in Northern Europe, Africa, South America and the Mediterranean, whereas the tropics present relatively low uncertainties. This is mainly associated with the uncertainties in downtime as a result of tropical cyclones, which are relatively small in our modelling framework (see Methods).

The resilience level of a port determines its risk profile. Resilience, in our analysis, includes the capacity of ports to operate under more extreme maritime conditions, the ability of ports to cope with hazard impacts (e.g. through improved engineering standards of infrastructure), and the measures in place to quickly recover after a hazard, thereby shortening the recovery duration (e.g. lead times of asset replacement, emergency preparedness). Given that the level of resilience is impossible to measure in a generalised way on a global scale, the sensitivity analysis helps to provide insights on how slight improvements, or the deterioration of, port resilience can influence port-specific and trade risk. Figure 6.4c-h illustrate the contribution of the engineering standards, recovery ability and operational resilience to the overall variance in the risk results. For the vast majority of ports, the port-specific risk estimates are mainly influenced by the engineering standards of the port and critical infrastructures (Figure 6.4c) and only to some extent by the recovery ability (Figure 6.4e). The importance of engineering designs was also identified as a major uncertainty in previous large-scale infrastructure risk analysis (De Moel, Asselman and H. Aerts, 2012; Koks *et al.*, 2019). The operational resilience, however, is very important for a number of ports, in particular those showing large relative uncertainties (Figure 6.4g). This illustrates that for those ports, being resilient against marine extremes, through improved operability under extreme winds and waves for instance, is a key factor in the overall risk these ports face. For instance, for the port of Port Elizabeth, which is at risk of facing frequent operational disruptions due to its high exposure to extreme waves, being able to operate under higher waves heights (e.g. tugs and pilot vessels that can cope with this) will significantly diminish the frequency of disruptions as a result of the exceedance of operational thresholds. This also underlines that these ports are sensitive to changes in these extreme conditions as a result of climate change.

Trade risk is sensitive to a more complex combination of contributors to resilience. In particular, the engineering standards are still important for cyclone-prone areas (Figure 6.4d), while recovery ability and operational resilience are dominant drivers of uncertainty in other parts of the world (Figure 6.4f and Figure 6.4h). Hence, whereas reducing the recovery duration and improving operability against climate extremes have limited effect on the port-specific risk (as logistics losses are relatively small), they are essential for the trade risk as they directly influence downtime. In light of these results, collecting local information on operational thresholds, recovery ability and engineering standards is extremely important to refine the risk estimates. For instance, a port survey by UNCTAD (UNCTAD, 2017a) illustrated that operational thresholds can vary considerably across ports, with critical wind thresholds varying by a factor of two to three between ports. Similarly, the critical coastal flood thresholds for continued integrity of the ports, reflecting the terminal deck elevation, ranges from zero to five metres.

6.3 Discussion

This paper presents the first comprehensive and systematic multi-hazard risk analysis of ports on a global scale, quantifying the physical damages to port and critical infrastructure assets, and logistics and trade losses due to natural hazard-induced port downtime. We find that most ports are exposed to several hazards that can cause significant damage and disruption. Globally, 86.2% of ports are exposed to more than three hazards, while around a fifth of the ports are prone to the impacts of five or six hazards (out of the six hazards considered). The large exposure of ports in north-western Europe to coastal flooding is in line with the work of Christodoulou *et al*. (Christodoulou, Christidis and Demirel, 2019), who also identified this region as highly exposed to present-day extreme water levels. The results presented by Izaguirre *et al*. (Izaguirre *et al.*, 2021), although mainly looking at operational thresholds of ports and not natural hazard impacts, show a similar pattern of high multi-hazard exposure in Japan, South-East Asia, the Gulf of Mexico region, and parts of Mexico. However, the inclusion of fluvial flooding, pluvial flooding and earthquakes in our study brings in additional nuances to the spatial distribution of natural hazard exposure. The exposure analysis underlines that port risk analysis should not just focus on one hazard, but should take a multi-hazard perspective. Future analysis should consider how these hazards may combine into compound (Bevacqua *et al.*, 2019) and/or consecutive disasters (de Ruiter *et al.*, 2020), or how multiple ports can be disrupted simultaneously (Verschuur, Koks and Hall, 2020) (Chapter 3), in particular when multiple hazards are driven by the same large-scale synoptic weather systems (e.g. winter storms in Europe).

The port-specific risk from damage and disruption at ports is found to be 7.6 (5-95th CI: 4.0 - 17.4) USD bn per year, mainly driven by cyclone wind and flooding (fluvial, coastal and pluvial). This global number is over half as large as a previous estimate of the physical asset risk of road and rail infrastructure on a global scale (Koks *et al.*, 2019), illustrating that although ports only encompass relatively small areas, the high value and density of assets can significantly contribute to the natural hazard risk to critical infrastructure on a national and global scale.

Out of the 1380 ports studied, 160 ports face a risk of more than 10 USD m per year, while 21 ports face a risk of more than 50 USD m per year. In absolute terms, port-specific risk is concentrated in large ports in high-income countries, given their extensive port areas and high infrastructure density, whereas the risk relative to port area is higher in small ports in low income countries. This poses a twin problem. On the one hand, large ports need to make significant investments to manage their risk in light of increasing risk due to climate change. For instance, by 2100, 12 to 63 USD bn is needed to elevate port terminals to accommodate rising sea levels (Hanson and Nicholls, 2020), which is already several times higher than the port-specific risk estimated in this study. On the other hand, infrastructure upgrades are needed to protect small ports in low-income countries from hazard impacts and frequent disruptions, which can have systemic impacts on economic growth in these countries. At small ports, the impacts of climate change on economic activity can be reduced by improvements to infrastructure to make them more disaster-resilient and ensure year-round operations. For instance, the Asian Development Bank financed several investment proposals to upgrade some of the outdated port infrastructure in Papua New Guinea (replacing and raising deck in Alotau port), Samoa (rehabilitating the breakwater, upgrading terminal infrastructure, and upgrading the tug boat of Apia port) and Niue (redesigning the wharf of Alofi port) (Asian Development Bank, 2020).

Although damage to port infrastructure is the main contributor to port-specific risk across ports, logistics losses and critical infrastructure damages cannot be ignored. For instance, risk due to critical infrastructure is significant in Europe and North America, mainly as a result of flood impacts that can cause bottlenecks to port functionality if critical infrastructure networks are disrupted. Flood risk management of critical infrastructure assets in the port's vicinity should therefore be an integral part of risk management. However, given that the ownership of port terminals (e.g. often owned by a terminal operators) and critical infrastructure (e.g. often owned by national or city governments) differ, and hence responsibilities for risk management, creating a port-wide risk strategy is essential to avoid misalignment between risk standards.

In addition to the potential for damage and losses at and around ports, we find that 0.8%, but up to 1.8%, of global maritime trade is at risk from disruptions every year. In particular SIDS are prone to trade risk, but also larger economies such as Taiwan, the Philippines and Vietnam. Cyclones are the main contributor to trade risk, as they can cause frequent downtime to ports, in line with previous literature (Verschuur, Koks and Hall, 2020; Y. Zhang *et al.*, 2020; Izaguirre *et al.*, 2021). Such maritime trade disruptions can further cause supply-chain losses on a global scale, which are not quantified in this study, but can be equally large or even larger than the asset damages (Koks and Thissen, 2016). For instance, a previous study has estimated that every dollar of maritime trade is associated with 4 dollars of global economic activity (Verschuur, Koks and Hall, 2022) (Chapter 5), emphasising that supply-chain losses can be significant, but are highly dependent on the resilience embedded in both the maritime network and economic system (Rose and Wei, 2013).

Finally, the sensitivity analysis not only highlights that the risk estimates are sensitive to the input parameters, but that the importance of certain parameters, especially the parameters reflecting the ports' resilience to hazard impacts, differs per port and risk metric. Efforts to assemble and share such resilience information, as already done by organisations such as PIANC (for instance the 'Navigating a Changing Climate' initiative) and UNCTAD (as done in the 'Port Industry Survey on Climate Change Impacts and Adaptation' (UNCTAD, 2017a)), should be enhanced in order to improve risk estimates and learn from best practices.

This study has demonstrated that it is now feasible to perform asset-level risk analysis to ports on a global scale provided a newly developed global datasets of port assets, global but locally refined hazard information at a port-level, and a new port trade database. This can help understand the scale and spatial footprint of risk, and facilitate the prioritisation of investment needs. Such information is highly relevant for a variety of stakeholders involved in the maritime supply-chain, including policy-makers, private-sector investors, insurance companies, and maritime operators. Moreover, this research paves the way for a complete assessment of the natural hazard risks to global maritime trade and supply-chains as a result of natural hazards at present and in the future. Further incorporating climate change into our unified analysis framework will enable quantification of the scale of global investment that will be required in adaptation measures, such as elevating port terminals, improving flood protection standards, or enhancing port-level resilience (e.g. improved engineering standards).

6.4 Methods

The methodology includes the following components: (1) the creation of a database of port and critical infrastructure, (2) the assumptions and approach for deriving the operational thresholds, (3) the assumptions and approach for performing the physical asset damage analysis and recovery duration for the five natural hazards (coastal flooding, river flooding, pluvial flooding, cyclone wind and earthquakes), (4) the assumptions and approach for performing the fault tree analysis to estimate the port downtime, (5) the assumptions and approach for estimating the logistic losses, (6) port-specific risk and trade risk estimation and (7) the methodological approach for incorporating the variance-based sensitivity analysis in the risk framework. On overview of all the input parameters and model assumptions is included in Supplementary Table A3.1.

6.4.1 Port and critical infrastructure database

The port and critical infrastructure database consist of the following assets: (1) port terminals and associated land-use, (2) critical infrastructure including road, rail, electricity and power plants, and (3) an estimated number of ship-to-shore cranes for container terminals. First, we manually mapped and classified more than 13,000 land-use areas across all ports considered using satellite imagery available in the QGIS software (Google Satellite). We classified port land-use areas into 15 port land-use types, which we further aggregated into seven main types (Container, Dry Bulk, General Cargo, Liquid, RoRo, Storage, Other). These land-use types are chosen as they can be easily distinguished from imagery, require specific handling equipment and have different reconstruction costs. Supplementary Table A3.2 provides an overview of the port land-use types and Supplementary Figure A3.4 shows examples for each port land-use type. Industry is often clustered around port areas or integrated within the port boundaries. We extracted the industrial land-use layer (polygons) included in OpenStreetMap (OSM), and manually checked if all industry facilities were included. If industry is missing, we supplemented the OSM data with manually mapped industry polygons. In total, over 2,000 industrial facilities are located in the vicinity of ports in our database. The land-use types Container, Dry Bulk, General Cargo, Liquid and RoRo are considered the essential port land-use types for operational purposes. Only ports for that have one industry land-use (and no port land-use), the 'industry ports', we considered this industry as the essential land-use for port operations. A breakdown of port areas per continent and comparison with previous work is included in the Supplementary Note A3.1.

Second, we included critical infrastructure assets within the port vicinity in the risk analysis. For every port, we added a buffer with a 1 km radius to the port and industrial land-use areas, which we define as the vicinity of a port. We also tested other buffer areas (ranging from 0.5 to 5km), with 1km being a compromise between including too many infrastructure assets (especially for ports close to city centres) or including too little (for ports in more remote areas). We hereby assume that these assets are critically important for the well-functioning of the port. Within the 1km buffer, we extracted the asset locations of roads from the GRIB database (Meijer *et al.*, 2018), rail networks from OSM data, electricity transmission lines from Gridfinder (Arderne *et al.*, 2020) and power plants from multiple external databases, including the WRI global power plant database (Byers *et al.*, 2019) and a global coal power plant database (Oberschelp *et al.*, 2019).

Third, we estimated the number of ship-to-shore cranes needed for container (off)loading, as they are susceptible to cyclone wind damage. The number of cranes is derived by first capturing the maximum daily number of container vessels per port (based on data reported in previous work (Verschuur, Koks and Hall, 2022), Chapter 5) and multiplying this with the average number of cranes needed per vessel (see Supplementary Table A3.1).

In Supplementary Figure A3.5, examples of geo-located port and critical infrastructure assets for six ports are shown.

6.4.2 Operational risk analysis

For the operational risk analysis of ports, we include wind speed, temperature, wave height and wave overtopping (referred to as marine extremes), similar as in Izaguirre *et al*. (Izaguirre *et al.*, 2021). We evaluate the average number of days per year a critical operational threshold is exceeded, which is the operational risk of downtime, and add the four downtime across the hazards to come up with the total operational downtime. We hereby assume that exceedance of an operational threshold leads to the closure of a port without any physical damages to the port or critical infrastructure.

The operational thresholds for temperature and wind have been derived in previous (Izaguirre *et al.*, 2021) and confirmed by port experts and others (Monioudi *et al.*, 2018; Verschuur, Koks and Hall, 2020), with threshold for wind speed set at 17 m/s and temperature set at 35ºC. However, for temperature, we add a threshold of 45ºC for countries in the Middle-East to reflect the local operational conditions. To get the exceedances of wind and temperature, historical time series (1979-2018) at every port centroid are extracted from ERA5 global reanalysis data (Hersbach *et al.*, 2020).

For waves and overtopping, we adopt two thresholds based on the exposure level of the port (normal exposure and high exposure), which reflect the distance to the coast, and the type of coastal protection in place (e.g. natural protection, breakwater, seawall). To get information on the breakwaters, we manually mapped and classified breakwaters from satellite imagery (classified as either coastal breakwater, seawall or inlet) for all ports in our sample (see Supplementary Text for a description). First of all, ports that are located inland (defined as being at least 20km from the coastline) are not exposed to the impacts of sea waves (some may be exposed to locally generated waves, but these are not included in the wave data). Second, ports that have an inlet breakwater are exposed to wave heights, but not to overtopping (since the port infrastructure is located inland). Third, ports that have a shelter characterized as ‘Excellent’ or a port type characterized as ‘River Tide Gates’, ‘Coastal Tide Gates’ or ‘Coastal Natural’ in the World Port Index (WPI), without an engineered breakwater, are assumed to be well sheltered and not exposed to waves and overtopping. All remaining ports are assumed to be exposed to waves and are assigned the normal exposure (NE) threshold, except ports that are considered a ‘Open Roadstead’ type in the WPI which are assigned the high exposure (HE) threshold, since they have no natural or engineered protection. For overtopping, all coastal breakwaters are assigned the NE threshold, while ‘Open Roadstead’ ports and seawalls are assigned the HE threshold.

For waves, the NE threshold is set to five metre and reflects the operational thresholds of pilot boats and safe manoeuvring of vessels when entering harbours, with coastal protection preventing against wave penetration inside the sheltered area. The HE threshold is set for ports where port operations and cargo handling is directly exposed to wave impact (e.g. some oil terminals). Here, we adopt a threshold of four metre, above which vessel (un)loading is limited. For wave overtopping, we set the wave overtopping threshold based on the type of coastal protection. A tolerable overtopping criteria of 0.4 l/s/m is adopted for seawalls (Sierra *et al.*, 2016) and 1 l/s/m for breakwaters (EurOtop, 2018). Seawalls often have port equipment or other critical port assets located directly behind the seawall and are therefore engineered with lower overtopping limits (EurOtop, 2018).

To derive the annual exceedances of wave and overtopping thresholds, additional processing steps are needed. We extracted wave parameters (significant wave height, wave period and wave direction) from ERA5 global reanalysis wave data at 6-h interval from 1979-2018 (Hersbach *et al.*, 2020). For every port, we extracted data at the closest grid cell and create a daily time series by selecting the wave parameters concurrent with the daily maximum wave height. This wave height is then propagated to the entrance of the port based on a simple wave propagation formula, similar as done in previous work (Izaguirre *et al.*, 2021). Interested readers are referred to the Supplementary Note A3.1 for details. Wave overtopping is estimated using the wave parameters, storm surge levels and the breakwater database. Given that detailed designs of breakwaters are not available on a global scale, we first create a synthetic breakwater design per port based on engineering design principles (in particular the crest height) and use these design criteria to estimate daily overtopping time series per port. Interested readers are referred to Supplementary Note A3.1 for the details of the methodology and Supplementary Figure A3.6 for the result of the crest height of the breakwaters.

6.4.3 Physical asset damages and recovery time

Physical asset damages are evaluated for five natural hazards: earthquakes, tropical cyclone wind, fluvial flooding, pluvial flooding and coastal flooding. We have developed separate methodologies for each of the hazard type as explained below. To estimate physical asset damages, we follow the standard approach in risk modelling by overlaying the hazard layer with the geolocation of the asset and assign a damage value to that asset based on asset-specific and hazard-specific fragility curves and the maximum (re)construction costs of the asset (Meyer *et al.*, 2013). Moreover, we estimate the recovery time associated with repairing or reconstructing the asset, which results in the downtime of the port. To estimate the downtime, we adopt recovery curves and apply these only to the essential port infrastructure and the critical infrastructure, as they are directly contributing to the operational functionality of the port. Recovery curves relate the fraction of damage to the number of days of recovery. We adopt a simple area or length weighted approach to estimate the port-wide fraction of damage. For instance, if 50% of the roads are 20% damaged, 20% of the roads are 100% damaged, and the other 30% remaining intact, the road damage to the port is 30% (0.5*0.2 + 0.2 * 1.0 + 0.3 * 0.0). An overview of the maximum damage values adopted are shown in Supplementary Table A3.1.

We use the earthquake hazard maps included in the UNISDR Global Assessment Report 2015 (UNISDR, 2015), which are based on a fully probabilistic seismic hazard model. The hazard maps depict the severity of ground shaping measured in peak ground acceleration (PGA) in cm/s^2 and are available for five return periods (250, 475, 975, 1500, 2475 years). Different fragility curves are defined for the different land-use types, which either reflect direct damage to the structure/buildings (e.g. warehouse, bulk, liquid) or to the quay walls (Container, General Cargo, RoRo). Moreover, earthquake fragility curves for the critical infrastructure assets are adopted (see Supplementary Table A3.1 for an overview of the sources). The earthquake recovery curves and maximum recovery days are based on FEMA's 2020 HAZUS Earthquake Technical Manual (FEMA, 2020b). The maximum port recovery duration adopted corresponds well with the recovery of the port of Kobe after the 1995 earthquake, which took almost two years to fully recover (Chang, 2000).

The impact of tropical cyclones (TCs) is measured only in terms of extreme wind speeds that affect port operations and cause damage to assets. To estimate the TC hazard, we make use of 10,000 years of synthetic TC paths per cyclone basin (Bloemendaal *et al.*, 2020). Each path represents a plausible tropical cyclone with location, wind speed, radius and pressure estimated every 6h from its origin until full dissipation. To estimate the wind speed at the port, we use a parametric wind speed model based on the Holland wind speed profile (Holland, 1980), which is the most widely used parametric formula. We use the formulation of Lin and Chavas (Lin and Chavas, 2012) to estimate the Holland parameter, with environmental pressure values taken from the AIR hurricane model (Butke, 2012). Out of the port infrastructure, only industrial facilities, liquid terminals, bulk terminals, and warehouses are assumed to be prone to wind impacts. For the critical infrastructure, road and rail infrastructure are assumed to be unaffected, in line with (Miyamoto International, 2019), while electricity and power plants are vulnerable to damage. Moreover, we include a fragility curve for ship-to-shore cranes, which are known to be susceptible to extreme winds. See Supplementary Table A3.1 for an overview of the fragility curves. Instead of using recovery curves for TC wind, we derive an empirical port recovery relationship. To estimate the duration a port is out of service due to a TC event, we fit a regression model based on observed port downtime due to TCs as reported in a port disruption database (Verschuur, Koks and Hall, 2020) (Chapter 3). This database includes 107 observations of port disruptions due to TCs leading to downtime across the world. The regression model we adopt includes the maximum wind speed, the duration (hours) above 15 m/s and 35 m/s, the distance between the eye of the TC and the port, and three dummy variables to include whether a port has good/bad shelter, is large/small and has pilot assistance or not. The 15 m/s and 35m/s thresholds are adopted as they roughly correspond to the serviceability and ultimate limit thresholds of ship-to-shore cranes. We estimate the variables based on the historical TC paths derived from the 'International Best Track Archive for Climate Stewardship' (IBTrACS) database (to match the TC to the one reported) and the method described above. The model fit is good ($R^2 = 0.75$), all variables are significant at $p = 0.1$ or lower except for the 15m/s threshold. The predicted and observed estimates are shown in Supplementary Figure A3.7, including the uncertainty of the fitted parameters. We adopt this regression model to estimate the downtime for all synthetic TC events and derive empirical return periods. We use the uncertainty associated with the prediction for the sensitivity analysis (see 'Sensitivity analysis').

Global fluvial and pluvial flood hazard maps are obtained from JBA consulting (https://www.jbaconsulting.com) who have created inundation maps for the port areas. Hazard maps for six return periods (20, 50, 100, 200, 500 and 1500 years) at 1 arcsecond resolution (~30m) are used for this analysis. We would like to refer to Aerts *et al.* (Aerts *et al.*, 2020) for an overview of the JBA global fluvial flood model and a comparison to other global fluvial flood models. For the fluvial flooding, we add protection standards from the FLOPROS database (Scussolini *et al.*, 2016) to the data and truncate return periods below the protection standards as they will not result in flooding. No protection standards are added to the pluvial flooding risk calculations, as drainage infrastructure is often only protected against ~10 year pluvial flood events (Canevari *et al.*, 2015), although some ports have higher engineering standards. However, given a lack of globally consistent data (and given that 20 years is the lowest return period), we do not adopt additional protection standards in the analysis. Fragility curves are based on a number of sources, as shown in Supplementary Table A3.1. The recovery curves adopted are similar as the earthquake recovery curves. However, the maximum recovery values are adjusted to reflect known recovery durations of ports. A maximum port recovery of 120 days is used, which is based on the time needed to reconstruct the port of New Orleans (Rousset and Ducruet, 2020) and the port of Mobile (Abdelhafez, Ellingwood and Mahmoud, 2021) after Hurricane Katrina, whereas the road and rail maximum recovery durations are based on the time spent to recover flooded railway lines in Australia that affected port operations at Port Walcott and the Port of Hay Point for ~45 days (Verschuur, Koks and Hall, 2020) (Chapter 3).

Coastal flood hazard maps are used in most previous global coastal flood risk analysis (Christodoulou, Christidis and Demirel, 2019; Koks *et al.*, 2019). However, these coastal flood maps are not well suited for coastal flood risk analysis of ports. First, the digital elevation model (DEM) included in such analysis often has a low resolution and does not adequately capture the elevation of port terminals at the sea-land boundary. Previous research, for instance, illustrated the sensitivity of inundation of port facilities in the U.S. Virgin Islands due to errors in the DEM (Bove *et al.*, 2020). Second, the extreme water levels (EWL) time series that is used for coastal inundation modelling includes assumptions on the EWL contributions (e.g. wave set-up) that are important for some ports but not for others (due to the presence of breakwaters). We therefore create our own EWL time series for ports based on the time series of different EWL components:

$$EWL = Tide + Surge + SLA + WS$$

with *Tide* representing the daily tide, *Surge* the storm surge, *SLA* the sea-level anomalies and *WS* the wave set-up for the port. The tide and surge time series are based on daily values from the Global Tide and Surge Model for 1979-2018 (Muis *et al.*, 2020). The *SLA* are taken from satellite altimetry data (1993-2015) on a monthly time scale (Ablain *et al.*, 2015). The importance of *WS* depends on whether a port is exposed to breaking waves, and whether or not a breakwater is in place. In line with the wave overtopping, we assume that ports that are not exposed to wave overtopping are also not exposed to WS from breaking waves. We also assume that ports located more than 20km from the coast are not exposed, since we cannot predict storm surges in tidal river channels or inland lakes. For port terminals that are exposed, the contribution of WS depends on the presence of a breakwater. If no breakwater is present, or a seawall is in place, we assumed WS to be 20% of the significant wave height ($0.2*H_s$) in line with previous work (Vousdoukas *et al.*, 2018). If a breakwater is present, the wave height inside the harbour area, the transmitted wave height, is equal to the outside wave height times the transmission coefficient K_t ($H_{s,t} = H_s * K_t$). We estimated $H_{s,t}$ using the Goda formula (Goda, Takeda and Moriya, 1967), which is often used in practise:

$$H_{s,t} = H_s * \frac{1}{2}\left[1 - sin\left(\frac{\pi(\frac{Rc}{Hs} + \beta)}{2\,\alpha}\right)\right]$$

with Rc denoting the breakwater freeboard and K_t bounded between 0 and 1 with α and β equal to 2.0 and 0.5 (Goda, Takeda and Moriya, 1967). Rc comes from the breakwater design established previously (Supplementary Figure A3.6). To estimate the return periods of EWL (2, 5, 10, 20, 50, 100, 200, 500, 1000, 5000), we used the GEV-6largest method (fit a GEV function to the 6 largest values every year), as it was shown that this method does not overestimate nor underestimate EWL compared to other approaches (Wahl *et al.*, 2017). In case this gives an unbounded fit, we used a GEV fitted to annual maximum EWL (GEV-A), or a Gumbel fitted to annual maxima if GEV-A gives unbounded results as well. To illustrate, the modelled 100 year EWL is shown in Supplementary Figure A3.8. To estimate the flood extent per return period, we overlayed the modelled EWL with the elevation of the port and hinterland infrastructure. We used the JAXA AW3D30 DEM model (Takaku *et al.*, 2020) with a 30m horizontal resolution to perform the analysis. The JAXA AW3D30 DEM was found to be the best performing DEM compared to other global DEMs based on an analysis of multiple geographical regions (Uuemaa *et al.*, 2020), and is particularly good in capturing the sea-land boundary accurately (Almar *et al.*, 2021). We adopt the same fragility curves and recovery estimates as used in pluvial and fluvial flood analysis. Coastal flood protection standards from Tiggeloven *et al*. (Tiggeloven *et al.*, 2020) are used in the analysis in a similar fashion as in fluvial flood risk analysis.

6.4.4 Port downtime

To derive a port-level recovery estimate, we performed a simple fault tree analysis (FTA) based on the recovery duration of the port and critical infrastructure assets. A FTA captures how disruptions to the port infrastructure assets lead to loss in functionality to the port as a whole. FTA have been used previously for detailed risk analysis of single ports (Abdelhafez, Ellingwood and Mahmoud, 2021). Here, we adopted a FTA with the essential port terminals, cranes, road, rail, power plants and electricity transmission as individual nodes in the failure tree. A failure to any of the nodes can reduce the functionality of the port (called an "OR" gate in FTA). Therefore, we estimate the recovery time per hazard and return period and set the largest downtime as the leading failure mode of the port.

Logistics losses

The logistics losses as a result of downtime consist of three components: the loss to port and terminal operators, the loss to shippers and the loss to carriers. Here, we used a simplified approach to estimate the logistics losses due to downtime in line with previous work (Zhang and Lam, 2015; Y. Zhang *et al.*, 2020). First, the port authority or terminal operator has a direct economic loss because when it cannot provide cargo loading/unloading services, for which they charge a fee per tonnes loaded or unloaded. The L_{port} can be written as:

$$L_{port} = c_{(un)load} f \Delta T$$

With $c_{(un)load}$ denoting the port charge per tonnes loaded/unloaded (USD/tonnes), f the daily freight flow in tonnes, and ΔT the number of days of downtime. Second, the shipper incurs losses because goods need to be stored (inventory loss) and there is a monetary values associated with time (value of time). The inventory loss is equal to the inventory costs per tonnes whereas the value of time is associated with the opportunity costs of the goods. In short we can write $L_{shipper}$ as:

$$L_{shipper} = If\Delta T + VOTf\Delta T^2$$

With I denoting the inventory costs per tonnes (USD/tonnes) and VOT the value of time (USD/tonnes/day). Third, the carriers suffer economic losses due to the risk of delayed delivery. This is assumed to scale with the freight rate of the goods. In short:

$$L_{carrier} = Ff\Delta T$$

With F denoting the freight rate of cargo per tonnes (USD/tonnes). The total logistics losses are the summation of the three individual factors. The values of the loading/unloading rate, the inventory costs and the freight rate are based on previous work (Zhang and Lam, 2015; Y. Zhang *et al.*, 2020). In reality, however, these values can vary between ports and regions. We will therefore test the sensitivity of these values. The estimated value of time and daily freight flows (in tonnes) are obtained from previous work (Verschuur, Koks and Hall, 2022) (Chapter 5).

6.4.5 Port-specific risk and trade risk

The port-specific risk includes the (1) physical asset damages to port infrastructure, (2) the physical asset damages to critical infrastructure and (3) the additional logistics losses due to downtime. For (1) and (2), we first aggregated the damages to the port-level per return period and hazard. Per hazard, we calculated the risk, expressed in terms of annual expected damages ($US/year), by applying the trapezoidal rule, and added the risk values up (ignoring any dependency between hazards). We then add the logistics losses associated with the operational downtime to the port-specific risk estimates.

Trade risk is defined as the amount of maritime trade (in monetary value) that is at risk of being disrupted annually. We can use the derived downtime estimates per natural hazard to find the annual expected downtime (number of days per year) by applying the trapezoidal rule and aggregating the downtime across hazards. The downtime associated with the operational thresholds is also added to this. We used this downtime metric to estimate the trade risk by multiplying the annual expected downtime with the estimated average daily trade value in a port, which is based on previous work (Verschuur, Koks and Hall, 2022) (Chapter 5).

6.4.6 Sensitivity analysis

A large number of assumptions and generalisations are made in the various model components. In order to capture the uncertainty in input parameters, and evaluate the sensitivity of the results to these uncertainties, we performed a large sensitivity analysis. To do this, we adopted a variance-based sensitivity analysis (Sobol sensitivity analysis) (Saltelli, 2002), which is implemented in the SALib python package (Herman and Usher, 2017). For every input parameter specified in Supplementary Table A3.1, we added an uncertainty range to the parameter (see Supplementary Table A3.1) and sampled 10,000 parameters from an uniform distribution function, except for the TC regression uncertainty, for which we used a normal distribution. We performed the sensitivity analysis for both the global estimates (port-specific risk and trade risk), as well as on a port-level (by running the algorithm for every port individually). The latter allowed us to explore the main drivers for the variance of the results globally and per port.

To evaluate the sensitivity of the resilience parameters, we sum the resulting variance contributions for a number of resilience related input parameters. For the 'Operational' indicator, we summed all input parameters related to the operational risk (e.g. thresholds, breakwater design parameter). For the 'Engineering standards', we summed the sensitivity measures of the depth-damage curves. The 'Recovery' indicator reflects all input parameters that affect the recovery duration, i.e. the recovery curves and the maximum recovery duration.

7 Climate risks to port infrastructure expansions for future global trade

Chapter 7 explores the need for new port expansions in the future under different trade scenarios that differ based on the degree of socio-economic development, decarbonisation and trade liberalisation. By projecting the evolution of climate risk into the future given climate change and port expansions, the future risks to port infrastructure and trade are quantified, as well as the planning uncertainties posed to new port expansions.

Paper: Verschuur, Li, Martinez, Koks, and Hall, Climate risks to port infrastructure expansions for future global trade, *to be submitted*.

Contributions: Jasper Verschuur: Conceptualization, Methodology, Formal analysis, Writing – Original Draft, Writing – Review & Editing, Visualization. **Sihan Li**: Resources, Writing – Review & Editing. **Luis Martinez**: Resources, Supervision. **Elco Koks**: Conceptualization, Writing – Review and Editing, Supervision. **Jim Hall:** Conceptualization, Writing – Review and Editing, Supervision

Data and code availability: The necessary data and code to reproduce all results will be published upon acceptance of the manuscript.

Abstract: Maritime trade is expected to grow significantly by 2050, requiring substantial new port infrastructure, a lot of which is being planned at present. Trade and climate uncertainty over this time frame pose risks to the design and financing of these infrastructure expansions. Here, using a new model of port expansions at 1380 ports worldwide and a model of global maritime transport, we predict that by 2050 an additional 1353-5735 km^2 of port terminals will be needed, requiring 1.3-5.6 USD trillion of investments. We further predict that climate risks to ports will grow from 6.5 USD billion per year at present to 16.0-37.4 USD billion per year in 2050 due to climate change (dominant factor for 50% of ports) and increased trade and infrastructure exposure (dominant for 50% of ports). We find the largest planning uncertainties in parts of Sub-Saharan Africa, India and South-East Asia, which are also areas with some of the largest investment needs. Whilst for some ports there is an opportunity to design new port infrastructure to be adapted to climate change at relatively low cost, other ports may experience inadequate future revenues to cover the costs of climate impacts and/or retrofits. Our results highlight the need to embed uncertainties in port infrastructure planning to manage investment risks proactively while adapting to a changing climate.

7.1 Introduction

Maritime transport is imperative for the global economy, transporting approximately 80% of global trade in terms of weight (Verschuur, Koks and Hall, 2022) (Chapter 5). Recent projections show that global maritime trade could increase three-fold by 2050 compared to 2015 (ITF, 2015; Walsh *et al.*, 2019), although the scale and nature of this increase is strongly dependent on the socio-economic and decarbonisation pathway (Walsh *et al.*, 2019). To meet this expected growth, a substantial amount of additional port infrastructure (i.e. quay walls, cranes, yard equipment) is needed (Hanson and Nicholls, 2020), which will require large public and private investments. At the same time, due to climate change, ports are increasingly exposed to both physical damages to port assets and operational downtime as a result of extreme weather events and chronic climate-driven changes (Christodoulou, Christidis and Demirel, 2019; Izaguirre *et al.*, 2021), which are equally dependent on the decarbonisation scenario.

Planning of new port expansions under large trade and climate change uncertainties is particularly challenging because of (i) the long planning horizons of new expansions (~20 to 30 years for port master planning) (Ligteringen and Velsink, 2012), (ii) the long lifetimes of port infrastructure (~30 to 100 years) (Becker *et al.*, 2013), and (iii) the irreversible and lumpy investments, i.e. they require large upfront costs and are expensive and technically difficult to retrofit when constructed (Taneja, Ligteringen and Walker, 2011). Faced with uncertainty in terms of trade, port expansions could become stranded (i.e. become obsolete or underutilised) or require additional upgrades soon after completion (Taneja, Ligteringen and Walker, 2011). Similarly, uncertainties in climate change projections could cause infrastructure to be over- or underdesigned. In the former case this would result in unproductive investment costs which could threaten a port's financial viability, while in the latter case it would result in excessive climate impacts and/or the need for costly retrofitting before the end of the intended infrastructure lifetime (Sriver *et al.*, 2018).

Although studies have looked at the present and future climate risks to port assets and operations (Christodoulou, Christidis and Demirel, 2019; Allen, McLeod and Hutt, 2021; Izaguirre *et al.*, 2021; Verschuur, Koks, *et al.*, 2022), the need for new expansions are ignored. Similarly, while an effort has been made to project the need for new port infrastructure on a country-level by 2050 (Hanson and Nicholls, 2020), it fails to include the likely locations of these expansions and their associated climate risks. Hence, to date, it is unclear how both trade and climate uncertainties come together at the port level, and which ports face the largest investment risk and planning uncertainty. This information is not only pivotal for port authorities and engineers, who plan, design and maintain the infrastructure, but also to determine the risks for those financing these port expansions. Given that many of the port expansions to meet demand for 2050 (and beyond) are being planned or constructed at present, there is an urgent need for this type of information to make sure investments are sound, and risks can be managed proactively.

In this study, we use an end-to-end modelling framework (that is from global trade to local infrastructure design) to estimate the need for new port expansions for 1380 ports to meet demand for 2050, and the climate risks and planning uncertainties associated with them. Specifically, we downscale 14 future maritime trade scenarios to the port-level using a global maritime transport model and feed these into a newly developed port planning and cost (PPC) model that estimates the required dimensions and construction costs of five terminal types (container, general cargo, RoRo, oil/gas, dry bulk terminals). This is combined with modelled climate risk (CR) associated with the occurrence of natural disasters (cyclones, flooding, earthquakes) and extreme weather-related events (wind, waves, temperature, overtopping) at present and for the mid-century time frame under different climate change scenarios. CR here refers to the risk of having to reconstruct damaged assets (i.e. physical damages) and the terminal revenue losses as a result of operational downtime. Altogether, it allows us to explore the future climate risk profile of port expansions and the planning uncertainties faced due to scenario uncertainty in terms of climate and trade.

7.2 Results

7.2.1 Future maritime trade at the port-level

We construct 14 coherent future maritime trade scenarios across 11 economic sectors for 2050 compared to 2015, which vary according to the degree of socio-economic development (SS1/SSP2/SSP5), decarbonisation (RCP2.6/RCP4.5/RCP8.5), which profoundly influences the volume of fossil fuel trade, and the degree of trade liberalisation (multilateral, Multi, or regional, Reg, scenario) (see Methods). These maritime trade scenarios are downscaled to the port-level using modelled maritime transport flows for 2015 using the Oxford Maritime Transport Model (OxMarTrans) (Verschuur, Koks and Hall, 2022) (Chapter 5), and grouped into aggregate throughput flow changes for the five main terminal types; container, dry bulk, liquid bulk, Ro-Ro and general cargo terminals. It is hereby assumed that the structure of the global maritime transport network does not change (i.e. no new trade routes or new ports), but instead, we evaluate the changing demand for the current sample of 1380 ports globally.

We find that under the SSP5 (4 scenarios), SSP2 (6 scenarios), and SSP1 (4 scenarios) scenario, the projected throughput growth is 60.6 – 86.7 billion tonnes (170 – 310% increase), 19.6 – 44.1 billion tonnes (70 – 160% increase) and 22.9 – 35.4 (80 – 120% increase), respectively (Figure 7.1a, see Supplementary Figure A4.1 for change per continent). Most throughput growth is expected at container, dry bulk and liquid bulk terminals, although dependent on the scenario (Supplementary Figure A4.2). While under the SSP5-RCP8.5 scenarios, there is an almost equal split between the three terminal types, under the SSP1-RCP2.6 scenarios (with less oil and mining products traded), the majority of throughput change is expected at container terminals.

The central estimate (mean across scenarios) of throughput change at the port-level shows a large increase in throughput in Sub-Saharan Africa, India, Indonesia and China, and low throughput growth in Western-Europe, Japan and the Middle-East (Figure 7.1b). The port throughput changes depend heavily on the trade scenarios (Supplementary Figure A4.3 highlights the scenarios that cause the highest and lowest throughput change). The lowest scenario varies widely per port (SSP1/2-RCP2.6-Reg most frequently), while the highest throughput scenario is most often the SSP5-RCP8.5-Multi scenario. Still, ports in for instance Scandinavia and New Zealand, among others, experience the highest throughput scenario under the SSP1-RCP2.6-Multi. Under this sustainability scenario, the world's energy system relies on biomass coming from timber-derived products (Walsh *et al.*, 2019), which are dominant trade flows at these ports.

20% of ports have at least one scenarios with a negative throughput change, while 5% of ports have a robust (at least seven scenarios) negative throughput (Supplementary Figure A4.4a). These ports are mainly concentrated in Japan, North America and Western and Northern Europe, potentially lowering port revenues or facing risk of stranded investments. On the contrary, 35% of ports have at least one scenario with rapid throughput growth (>300%), and 7% a robust rapid growth (Supplementary Figure A4.4b), in particular ports in Western Africa, Eastern Europe, and parts of Asia.

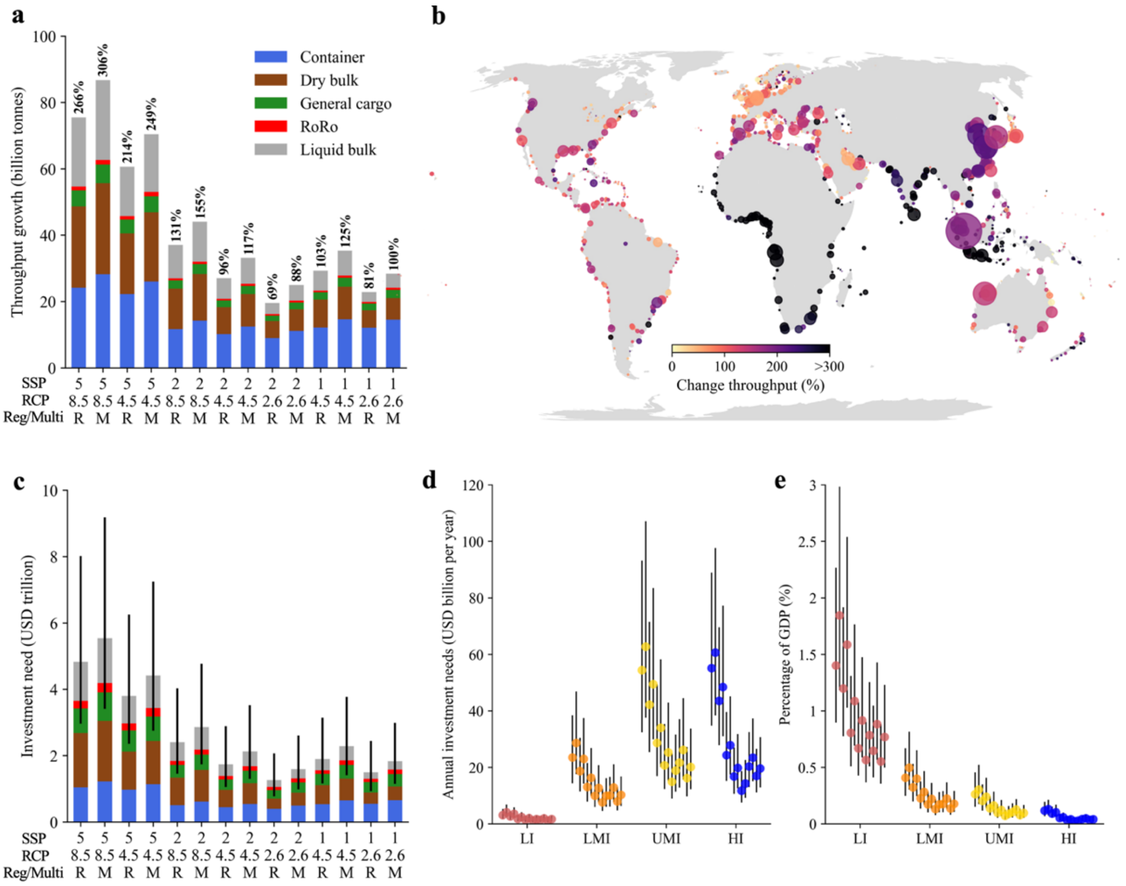

Figure 7.1: Port throughput scenarios and infrastructure investment needs. (a) Expected throughput growth globally per trade scenario and per terminal type. The number on top of the bar chart indicates the percentage change compared to present-day throughput. (b) The mean change in port throughput across all trade scenarios for 2050 compared to 2015. (c) Expected investment need in USD trillion to meet trade demand in 2050 per trade scenario and per terminal type. (d) The annual average investments needs in USD billion for the period 2015 to 2050 aggregated per income group per trade scenario. (e) The annual average investments needs as fraction of Gross Domestic Product (GDP) for the period 2015 to 2050 aggregated per income group per trade scenario. In (c-e), the uncertainty bar show the 10 to 90th percentile confidence interval based on the Monte Carlo analysis (Methods). LI: low income countries, LMI: lower middle income countries, UMI: upper middle income countries, HI: high income countries.

7.2.2 Port expansion and investment needs

The port-level throughput scenarios are fed into the PPC model (Methods), an engineering planning model based on design rules of port terminal dimensions and costs. Following common practise in port planning, we run the model probabilistically (N = 5,000 times) by specifying a range per input parameter, ending up with median value and a confidence interval (CI: 10^{th} to 90^{th} percentile) of the area and investment need per terminal type. We also perform a robustness check of the model results when various terminal efficiency scenarios are considered (see Methods), which only marginally change the results.

The infrastructure expansion needs are estimated to be 3992 – 5735 km^2 (2372 – 9660 km^2) under SSP5, 1353 – 2963 (815 – 5000 km^2) under SSP2, and 1591 – 2391 km^2 (962 – 3984 km^2) under SSP1 (Supplementary Figure A4.5). These values are broadly in line with Hanson and Nicholls (Hanson and Nicholls, 2020), who used a similar (though simpler) modelling framework and estimated the area need to be 1150 - 3700 km^2 in 2050 relative to 2010. Compared to the present-day total port area, which is approximately 5430 km^2 as mapped by Verschuur *et al*. (Verschuur, Koks, *et al.*, 2022) (Chapter 6), the global port area is projected to increase 25 – 106% in size by 2050. The investment needs necessary to finance these expansions (Figure 7.1c) are found to be 3.8 – 5.6 (2.4 – 9.3) USD trillion for the SSP5 scenarios, 1.3 – 2.9 (0.8 – 4.8) USD trillion for the SSP2 scenarios, and 1.5 – 2.3 (1.0 – 3.8) USD trillion for the SSP1 scenarios (Supplementary Figure A4.6 shows the relative contribution across terminal types). The global investment needs are in line with the Global Infrastructure Outlook (Oxford Economics, 2017), who forecasted infrastructure investment needs to be 3.2 trillion between 2015 and 2050 (by extrapolating their 2040 forecasts).

We aggregate the average annual investment needed between 2015 and 2050, further referred to as the (undiscounted) annual investment need (AIN), to country income groups (according to the 2021 World Bank country classification). In absolute terms, the AIN for high income (HI) and upper middle income (UMI) countries (median 11.9 – 61.3 and 15.1 – 63.6 USD billion per year) are much larger than for lower middle income (LMI) and low income (LI) countries (median 4.9 – 47.6 and 1.3 – 4.2 USD billion per year) (Figure 7.1d). However, expressed as fraction of Gross Domestic Product (GDP), we find the relative AIN to be 0.03 – 0.13% (0.02 – 0.21%) for HI countries, 0.07 – 0.31% (0.05 – 0.52%) for UMI countries, 0.13 – 0.50% (0.09 – 0.83%) for LMI countries, 0.56 – 1.86% (0.36 – 3.02%) for LI countries (Figure 7.1e). Several countries have to make investments >5% of their GDP under some scenarios (e.g. Benin, Mozambique, Seychelles, Djibouti, Togo). It should be noted, however, that this need is not fully attributed to a change in maritime trade for the country itself. For instance, almost all of Ethiopia's trade is through the port of Djibouti, explaining the large AIN compared to its GDP (Ethiopia's GDP is >30 times that of Djibouti). Similar, the port of Lomé (Togo) serves as a main port for Niger, Burkina Faso and Mali (together >7 times the GDP of Togo).

The large investment need for LI countries indicates that this cannot solely be financed by public expenditure. However, at the moment, private participation in port investments in lower and middle income countries is only 3.8 USD billion per year (average over 2010-2019 based on the World Bank PPI database (World Bank, 2021)), which is 11 - 40% of the need in LI and LMI countries (ignoring UMI countries). In addition, for 36 OECD countries, the AIN is 9.5 - 51.0 USD billion per year compared to the existing annual public expenditure of 12.2 USD billion per year (based on the OECD database, Supplementary Figure A4.7). This underlines that under some scenarios, advanced economies experience similar shortfalls in public investments.

7.2.3 Climate risks

The occurrence of natural disasters (cyclones, floods, earthquakes) and marine extremes (wind, waves, temperature, overtopping) (henceforth called hazards) can cause physical damages to the port assets and operational downtime to the port as a whole. The need for new port expansions could increase the consequences of hazard impacts by having more physical assets and maritime trade (hence larger revenue losses) potentially exposed to damage and downtime, respectively. Additionally, climate change may alter the occurrence of these hazards (except earthquakes), which can further increase the CR to ports. We project the implications of a changing climate on the occurrence of hazards under three decarbonisation scenarios (RCP2.6/RCP4.5/RCP8.5) for 2050, which we pair with the respective throughput scenarios to evaluate changing CR (Methods)

Under climate change alone, the CR is projected to increase from 6.5 USD billion per year to 14.2 USD billion per year under RCP8.5, 10.9 USD billion per year under RCP4.5 and 11.3 USD billion per year under RCP2.6. The largest change in CR is observed for ports in southern Japan, the Middle-East, western Europe and New Zealand (Supplementary Figure A4.8). The combined effect of port expansions and climate change will further amplify the CR. As shown in Figure 7.2a, the globally aggregated CR reaches 24.3 – 37.4 (20.3 – 48.9) USD billion per year under SSP5, 16.0 – 26.3 (14.6 – 32.3) USD billion per year under SSP2, and 16.7 – 18.8 (15.1 – 22.8) USD billion per year under SSP1 (Supplementary Figure A4.9 shows the results per continent). Even though physical asset damages contribute most to CR (78 - 82%), operational downtime puts 0.28 – 0.76 billion tonnes, worth 229.6 – 504.9 USD billion, of throughput at risk every year (0.6 – 0.7% of global throughput, see Supplementary Figure A4.10). This can results in significant revenue losses, which is the dominant CR driver for 9.6 – 12.2% of ports globally.

The central estimate of the CR change at the port-level shows that ports in Africa, South America, the Middle-East, Indonesia and New Zealand will experience the largest combined CR change (Figure 7.2b). Climate change is the dominant driver for around 50% of ports spread around the world (Figure 7.2c shows the scenarios where climate change is the dominant driver), with clusters found in western Europe, Scandinavia, Oceania, the East Coast of North America and the Middle-East. Hence, the change in CR is determined by the local context and even within countries, large differences can be observed in terms of the relative importance of climate change versus expansions.

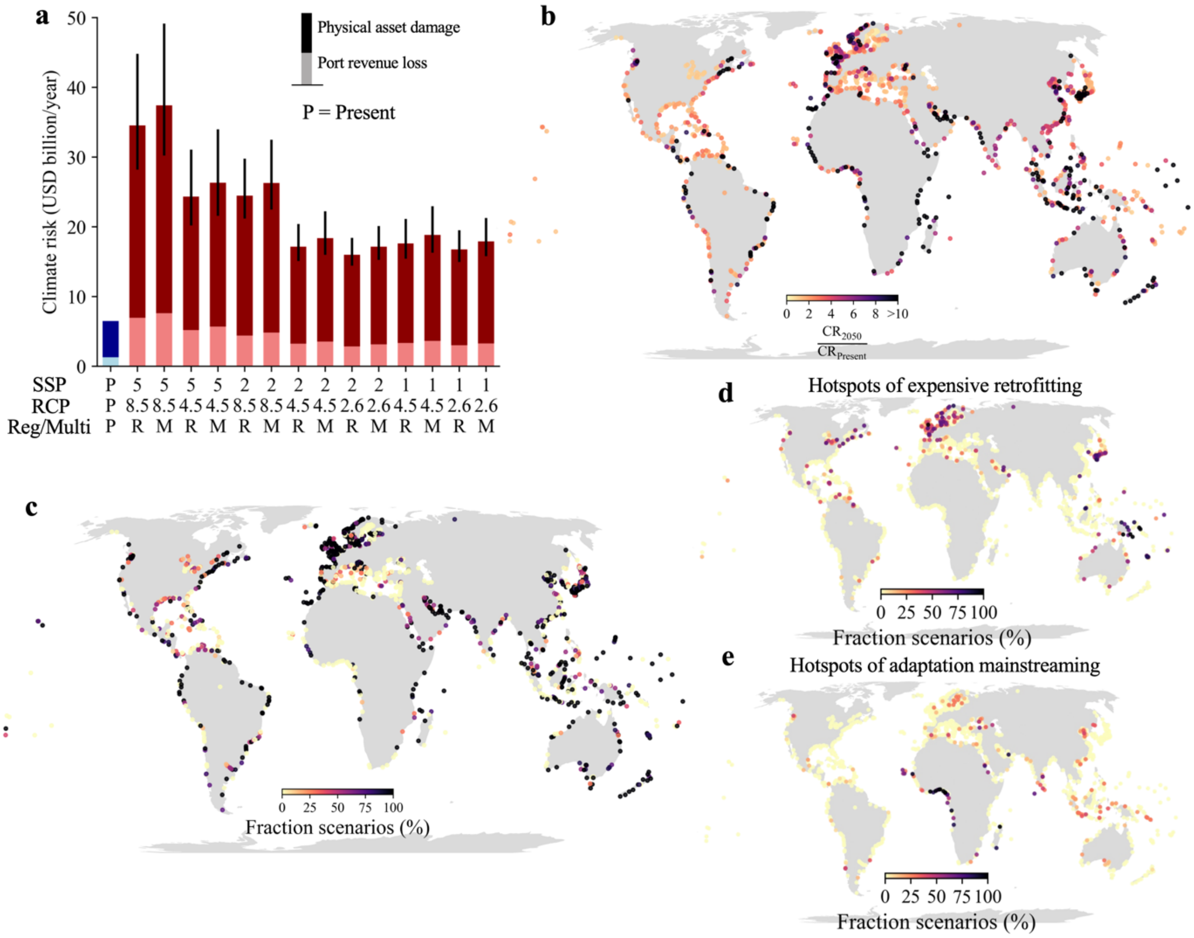

Figure 7.2: Future climate risks due to climate change and port expansions. (a) Globally aggregated CR, split by port revenue loss and physical asset damages, for the present (P) situation and under the 14 future scenarios. The uncertainty bars show the 10 to 90th percentile confidence interval based on the Monte Carlo analysis (Methods). (b) The mean future climate risk across the scenarios compared to the present-day CR. (c) The fraction of scenarios where climate change is the dominant driver (compared to port expansions) of future climate risk. (d) Hotspots of expensive retrofitting, showing the fraction of scenarios where throughput change <50% and CR >10 times AIN. (e) Hotspots of adaptation mainstreaming, showing the fraction of scenarios where throughput change >300% and AIN >10 times CR.

7.2.4 Mainstreaming adaptation

Port authorities have to set budgets aside annually to manage CR and plan new port expansions (CR + AIN). Globally, the AIN are 2.2 – 4.7 times larger than the CR. Still, CR is larger than the AIN for 30% of ports, concentrated in the Caribbean, Oceania, Japan and Western Europe (Supplementary Figure A4.11). Ports with low expected throughput change (<50%) and high CR ratios (CR >10 times AIN) may struggle to invest in adaptation as revenues only marginally grow or decrease, and adaptation measures are limited to expensive retrofitting. 21.8% (8.0%) of ports meet this criteria for at least one (seven) scenarios (Figure 7.2d), most of which are in Canada, Western and Northern Europe, Japan and parts of Australia. On the other hand, ports with large expansion needs (throughput change >300%) and low CR ratios (AIN >10 times CR) have the potential to mainstream adaptation of port infrastructure (both new and existing) into these investment decisions at relatively low additional cost. In total, 13.3% (2.4%) of ports meet this criteria for at least one (seven) scenarios, with hotspots in Western Africa, Sri Lanka, Eastern Europe and northern China (Figure 7.2e). In Supplementary Figure A4.12, we evaluate the sensitivity of this result to different criteria, showing consistent spatial patterns.

7.2.5 Planning uncertainties

While planning uncertainties are inevitable in large infrastructure projects, they may pose risks to the design and financial viability of the project. To understand what planning uncertainties dominate, we map whether ports face relatively more climate uncertainty, trade uncertainty, or both (Methods) (Figure 7.3). Parts of Oceania, South-East Asia, the eastern part of North America, and Western and Northern Europe face predominantly climate uncertainty but limited trade uncertainty. In these regions, ensuring that designs are climate-robust, meaning that they perform well under a range of climate scenarios (Hall *et al.*, 2012), is essential. Ports in the Mediterranean, the Black Sea region, the Gulf of Mexico, Chile and Western Africa face large trade uncertainty. For most ports, this is mainly attributed to their reliance on oil, refined petroleum products and mining goods, with future trade through these ports shaped by the composition of the future energy mix that depends on the level of decarbonisation (Walsh *et al.*, 2019). For these ports, incorporating flexibility into port planning and design, which implies incremental developments, designing for future retrofit, and timely review when new information becomes available (De Neufville *et al.*, 2008) helps to avoid stranded assets or insufficient capacity upgrades (e.g. as done by Port of Rotterdam for its Maasvlakte 2 port expansion project (Taneja, Ligteringen and Walker, 2011)). Most importantly, ports in Sub-Saharan Africa, India, South-East Asia and parts of China and Brazil are facing both climate and trade uncertainty. In the regions, investments face the largest risks in terms of generating the expected financial returns, requiring careful analysis to make sure such financial risks are incorporated in the investment decision.

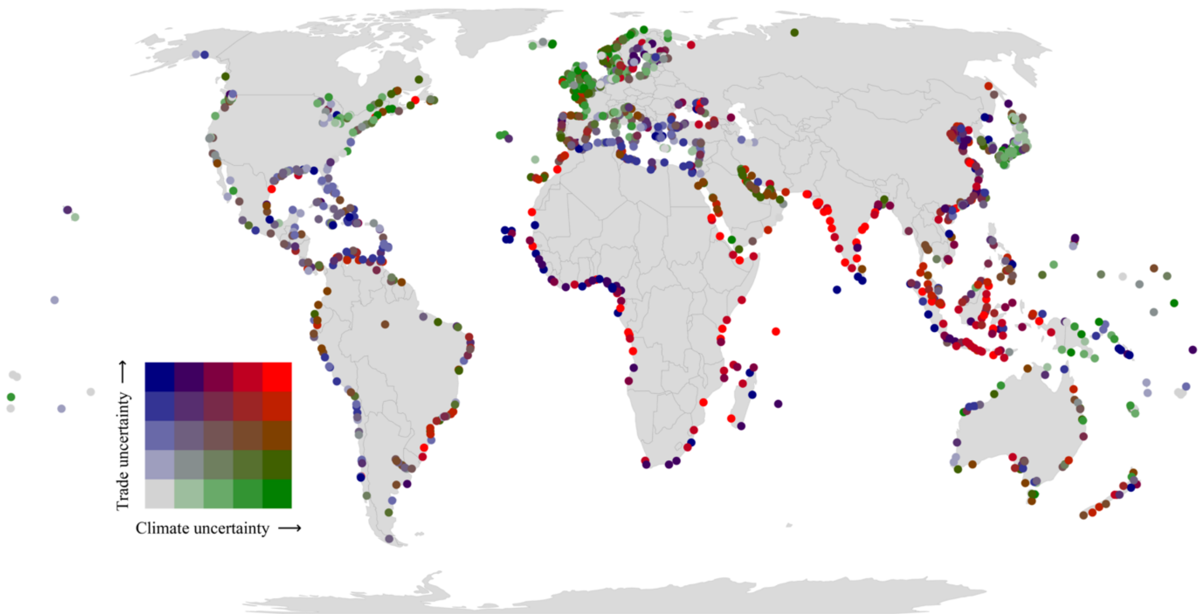

Figure 7.3: Planning uncertainties associated with climate change and trade. Relative climate change uncertainty and trade uncertainty per port by applying quantile mapping (five quantiles) of the relative uncertainties (see Methods).

7.2.6 Conclusion

We have demonstrated the need for, and benefits of, a multi-scale systems approach to climate-infrastructure risk analysis and adaptation planning. In particular, our end-to-end methodology, that is global in scope whilst also being spatially resolved down to the scale of individual infrastructure assets, has enabled the quantification of the relative significance of climate and economic uncertainties.

We find the investment required to finance port expansion to be vast: in the range of 1.3 - 5.6 USD trillion, and in relative terms >10 times and >5 times higher in LI countries (0.6-1.8% of their GDP) compared to HI and UMI countries, respectively. Hence, a large investments gap exist for LI countries (although also some HI countries), urging the need to scale up both public and private investments to bridge this gap. At the time, the CR increase by factor 2.5 – 6 due to climate change and these expansions. If major impacts from climate change to the global economy are to be minimised, it is essential to adapt port infrastructure to the anticipated impacts of climate change. Though we have not quantified the costs of adapting existing port infrastructure (e.g. raising quay walls or strengthening breakwaters), these costs are known to be very high compared to the cost of designing new infrastructure to resist anticipated changes in climate hazards. Thus, it should be easier and less costly to adapt to climate change in ports that will be growing in the future (we find that 35% of ports could experience >300% growth) compared to the 20% of ports where we predict that trade flows could decline.

We have demonstrated the scale, and relative influence, of uncertainties in climate and trade projections. Yet it is not clear that these uncertainties are being taken into account in the big port expansion plans that are currently under way. For instance, large port expansions are being planned across African ports (e.g. container terminals in West

Africa (Kinyua, 2020)), India (e.g. the 82 USD billion Sagarmala program of seaport investments implemented by 2035 (The Economic Times, 2021)), and South-East Asia (e.g. Belt and Road Initiative, with ~40 USD billion already invested in South-East Asian ports (Cox *et al.*, 2018)), which are also hotspots where trade and climate uncertainty collide. Hence, new decision-making frameworks, that incorporate robustness and flexibility in planning and design (Taneja, Ligteringen and Walker, 2011; Sriver *et al.*, 2018), have to become more embedded within the port planning process (Becker *et al.*, 2013, 2018; Sweeney and Becker, 2020) if the impacts of climate change on global trade are to be minimised, and port investors are not to be deterred by the scale of future risks and uncertainties that we have calculated.

7.3 Methods

7.3.1 Trade projections

The need for port expansions is determined by changes in future trade. We make use of several future trade scenarios for 2050, which vary by the degree of trade liberation, climate mitigation and socio-economic development. The baseline scenarios are based on the output of the OECD-ENV Linkages model, a dynamic computable general equilibrium model with a global coverage that predicts sector-specific international trade flows between 25 regions and for 26 economic sectors (of which 18 commodity sectors) (Château *et al.*, 2014). Here, we use projected trade flows for 2050 compared to 2015. These projected are bias-corrected based on observed trade growth in 2020 and 2021, which was less than the model predicts as a result of stagnated trade growth due to COVID-19. We use two trade liberalisation scenarios; one where developed economies embark on an ambitious regional agreement that phases out tariffs and frictions to trade in goods (Reg), and one where the world economies pursue a level-playing field for trade in goods by cutting tariffs on goods on a multilateral basis (Multi) (Château *et al.*, 2014).

Maritime trade predictions for various socio-economic development scenarios (SSP1, SSP2 and SSP5) and climate change scenarios (RCP2.6, RCP4.5 and RCP8.5) are taken from Walsh *et al*. (Walsh *et al.*, 2019). Instead of using absolute values from this study directly(which are based on scenario development and not explicitly GCE modelling), we use sector-specific scaling factor of global trade for 2050, and use this to create alternative scenarios by applying these scaling factors to the OECD-ENV trade scenarios. We hereby assume that the OECD-ENV baseline scenario corresponds to a continues growth scenario (SSP5). Only combinations of SSP and RCP that have shown to be feasible within Integrated Assessment Models are adopted (based on Rogelj *et al*. (Rogelj *et al.*, 2018)) This results in a set of 14 trade scenarios (seven combinations of SSP-RCP and two trade liberalisation scenarios), which capture the plausible bandwidth of future trade.

We use the growth factors (bilateral trade between regions in 2050 compared to 2015) to model future maritime trade between ports, assuming that the distribution of trade across ports remains constant. That is, we do not incorporate new routes or new ports in the model but look at the change in throughput for the set of ports considered. The 2015 throughput values for 1380 port globally for 11 economic sectors are taken from the Oxford Maritime Transport model (Verschuur, Koks and Hall, 2022) (Chapter 5), a global maritime transport model that predicts the amount of maritime trade flows between countries and its allocation on the maritime transport network, including which ports are being used for importing, exporting and the transhipment of these flows. By combining the growth factors per country-pair and sector with the modelled port-to-port trade network used to ship these goods, we can project the expected change in throughput per port into the future.

7.3.2 Port planning and cost model

The design of port terminals usually consists of different phases. The initial planning phase, the port's master planning (Ligteringen and Velsink, 2012), encompasses the conceptualisation of new port expansions plans based on basic terminal designs under various throughput scenarios. This initial project feasibility stage determines the likely area that needs to be set aside (or reclaimed) and the likely investments necessary to finance these expansions, capturing the long-term infrastructure development plan of the port for the next 20 to 30 years (Ligteringen and Velsink, 2012). Later on, these plans are translated into a more detailed design proposals based on detailed site investigations and a refined nautical, hydraulic and cost analysis. For the design of port terminals in the initial planning stage, no official (international) regulations are available. Instead, port terminals are often designed based on various design rules or predictive formulas.

Here, the need for port expansions is determined by feeding the future throughput change scenarios into a newly developed port planning model, the Port Planning and Cost (PPC) model, which is based on generalised engineering formulas used for port planning purposes. The expansion need in terms of port area covers the total port area, which include the quays, yard, apron, storage, and general areas (e.g. offices, etc.). The predictive area formulas depend, among others, on the amount of throughput, the dwell time of cargo, and various other factors related to the technological efficiency of the terminal and the cargo handled. The investment need covers the construction costs of the terminals, which comprise the civil works (e.g. quay wall, pavement), the land and (un)loading equipment, as well as additional indirect costs (e.g. mobilisation, administration and engineering costs), and contingencies. Other cost components, such as those associated with breakwaters, roads and buildings are not included, as their need depends on the local context.

We distinguish between five terminal types (container, general cargo, Ro-Ro, liquid bulk and dry bulk terminals), which all have different area requirements, cost components and design criteria. A similar approach has been followed in Hanson and Nicholls (Hanson and Nicholls, 2020) to determine area needs, although they only distinguish between container and general cargo terminals. The conversion from throughput to terminal type is based on a conversion table derived in earlier work (Verschuur, Koks and Hall, 2021a), which maps trade flows associated with a particular type of sector to the type of vessel, and hence terminal type, that is used for transporting and handling this trade.

Area and cost requirements can differ widely between ports and countries, depending on various parameters, and therefore have large uncertainties. In line with common practise in port planning (in particular in the initial planning phase), we run a probabilistic analysis that explores many possible combinations of input parameters between upper and lower bounds taken from the literature. We use quasi-random Monte Carlo analysis, with estimates converging at a sample size of N = 5,000. The generalised formulas and the range of input parameters used are described in the Supplementary Note A4.1 and Supplementary Tables A4.1-4.

As external validity check, we compare our modelled unit area requirements (tonnes per m^2) and unit construction costs (USD per m^2) to various external data sources, as described in Supplementary Note A4.2, finding that our PPC model is able to make realistic first-order estimates of port area needs and associated construction costs.

7.3.3 Terminal efficiency

The PPC model assumes that port will directly expand beyond current operational capacity and ignores that port terminals might be underutilised at present. However, as found by Merk and Dang (Merk and Dang, 2012), many ports are considered inefficient, in particular dry bulk ports. Improving terminal efficiency would in theory lower the need for additional expansions. Therefore, as robustness check, we also evaluate the effect of three terminal efficiency improvement scenarios (TEIS) in the model.

To do this, we estimate the existing terminal efficiency (*TE*) of ports per terminal category (*c*), which is derived from the average weekly (w) deadweight tonnage (*DWT*) called at the port compared to the weekly maximum DWT called over the period 2019-2020. This is based on actual vessel movement data using Automatic Identification System (AIS) data derived in earlier work (Verschuur, Koks and Hall, 2021a). We relate the TE to the utilisation rate of the port terminal:

$$TE = 100 * \frac{DWT_{w,c}}{DWT_{w,max,c}}$$

In other words, ports that have higher utilisation rates require more efficient terminal operations to handle the constantly high flow of goods. The TE differs widely between ports and terminal types, with container terminals often operating at TE rates than other terminal types. We can create different terminal efficiency improvement strategies (TEIS) by looking at the current TE of ports and hypothetically increasing this to higher levels as achieved by some of the most efficient ports globally. We consider three TEIS:

- Low TEIS, where ports that perform less than the 50th percentile globally can improve terminal efficiency to this level.

- High TEIS, where ports that perform less than the 95th percentile globally can improve terminal efficiency to this level.
- Maximum TEIS, where ports with an utilization rate less than 85% can boost terminal efficiency to this level, which is seen as the maximum operational efficiency level as observed from the data.

The percentile change between the existing TE and the TEIS is the reduction in demand for new port expansions. The reduction in area and investment needs are included in Supplementary Figure A4.13, showing that one can only reduce the area and investment needs under a very ambitious TEIS scenario, which is likely infeasible for many ports. The low sensitivity is mainly attributed to the fact that most throughput is concentrated in a small subset of very large ports which already operate at high terminal efficiency.

7.3.4 Climate risk

The climate risk (CR) metric we adopt throughout refers to the combination of physical asset damages and lost port revenue due to downtime. Physical asset damages refer to the monetary damages to assets as a result of natural disaster impacts. Physical asset damages are commonly derived by overlying the location of an asset with the occurrence of a hazard, and combining this with the vulnerability of the asset to this hazard and the costs to reconstruct it (Meyer *et al.*, 2013). Here, assets refer to different port terminals, but also include roads, electricity lines, railways, warehouses and industrial facilities located within the port boundary (see Chapter 6 for details). On top of that, ports face downtime risk associated with the time it takes to reconstruct assets or because operations have to shut down because an operational threshold is exceeded (Izaguirre *et al.*, 2021). This can result in revenue losses to terminal operators, who receive revenue from the loading and unloading of goods.

We consider five types of natural disasters; fluvial flooding, pluvial flooding, coastal flooding, tropical cyclone wind, and earthquakes. Moreover, we consider operational disruptions due to waves, temperature, wind and overtopping. The present-day CR estimates for the 1380 ports globally are derived in previous work (Verschuur, Koks, *et al.*, 2022) (Chapter 6). This work performed an asset-level risk analysis for the five types of natural disasters, as well as estimating the downtime to reconstruct the damaged assets. Physical asset risk refer to the expected average costs to reconstruct damaged port assets per year (in USD per year). Moreover, in terms of operational downtime, this work evaluated the number of days per year specific operational thresholds are exceeded due to overtopping and extreme winds, waves and temperature. Hence, downtime risk (*DR*), the expected average yearly days of downtime (number of days per year), is both associated with reconstruction time of assets due to natural disaster impact as well as operational downtime. The revenue loss (*RL*, in USD per year) under one of the 14 scenarios (s) is derived by multiplying the *DR* with the average daily throughput (*T*, at present or in the future) and revenue derived from handling these goods (i.e. often called wharfage dues, *WD*, in USD per tonnes):

$$RL = \frac{T_s}{365} * DR_s * WD$$

The *WD* are based on previous work (Y. Zhang *et al.*, 2020) and on reported *WD* from multiple port authorities. It should be noted that *WD* often differ per type of good and between ports, which are not considered here.

We further project the change in *CR* as a result of climate change by 2050 under different RCP scenarios (RCP2.6, RCP4.5 and RCP8.5). We do this by deriving climate change scaling factors for the four hazards that are expected to change because of climate change (earthquakes are assumed to remain constant). Similarly, we evaluate the exceedance of the four operational thresholds in the future to derive the future *DR*. We do this based on different methods, as summarised in the Supplementary Note A4.3.

The future *CR* under one of the 14 scenarios (*s*) is derived by scaling the physical asset risk (*PAR*) with the increase in existing port area (*PA*) due to port expansions (*PE*) and estimating the future *RL* due to growing *T*.

$$CR_{2050} = PAR_{present} * \frac{PE_s + PA_{present}}{PA_{present}} + RL\left(T_{2050,s}, DR_{2050,s}\right)$$

7.3.5 Planning uncertainties

We map ports as being relatively more exposed to climate uncertainty, trade uncertainty or both. The climate uncertainty captures the uncertainty in future CR (due to climate change alone) relative to present-day CR under the three RCP scenarios (*r*):

$$Climate\ uncertainty = \frac{max\, CR_{2050,CC,r} - min\, CR_{2050,CC,r}}{CR_{present}}$$

The trade uncertainty reflects the future trade uncertainty under the 14 scenarios (s):

$$Trade\ uncertainty = \frac{max\, T_{2050,s} - min\, T_{2050,s}}{T_{present}}$$

We rank the uncertainty per port and group ports in five equally sized groups (quintiles) to show the relative climate and trade uncertainty faced by ports globally.

8 SYNTHESIS

The synthesis of this thesis covers (i) a brief summary of the findings for every research question posed, (ii) a discussion focusing on a number of overarching points of reflection, (iii) recommendations for future research, and (iv) a concluding statement.

8.1 Summary of thesis findings

The aim of this thesis was to quantify present-day and future climate risks to port infrastructure and dependent trade flows using an integrated maritime-economic systems framework. To achieve this overarching aim, a number of research questions were posed, which were subsequently addressed in the respective thesis chapters:

1. What is the empirical evidence of past port disruptions due to natural disasters and the resilience of the maritime transport network?
2. What are the necessary elements of a global systems framework of the coupled maritime and economic networks, and how are they interconnected?
3. What is the criticality of ports in international trade and global supply-chains?
4. What are the present-day climate risks to global port infrastructure and the resulting logistics and trade losses?

5. What are the future climate risks to port infrastructure and trade as a result of climate change and the need for new port expansions, and how does this affect the design and planning of new port expansions?

A brief summary of the findings for every research question is provided.

8.1.1 What is the empirical evidence of past port disruptions due to natural disasters and the resilience of the maritime transport network?

Chapter 3 presented empirical evidence of past port disruptions and insights into port and logistics resilience. To do this, empirical vessel tracking data was used to analyse past port disruptions due to natural disasters, evaluating 141 incidences of disruptions across 74 ports and 27 disasters. The results showed that port disruptions have a median disruption duration of six days with a 95th percentile of 22.2 days if the event led to a full closure, and five days with a 95th percentile of 11 days if ports were not fully closed. An in-depth analysis of the studied disruptions highlighted a couple of lessons learned. First, some of the largest disruptions were associated hinterland transport networks being affected, alongside minor disruptions to the port itself. Second, all analysed events show multiple ports being affected simultaneously, challenging some of the studies that only focus on single port disruptions. Third, the duration of the disruption was found to scale with the severity of the event, with an increment of 1.0 metre storm surge or 10 metre per second wind speed being associated with a two day increase in the disruption duration. Fourth, in contrast to commonplace assumptions in model studies, substitution between ports is rarely observed during short-term disruptions, whereas on the other hand, production recapture happened in practice in many cases of port disruptions. In short, empirical vessel tracking data provides valuable insights for future modelling studies in order to better approximate the extent of the disruption and the potential resilience of the port and maritime networks.

8.1.2 What are the necessary elements of a global systems framework of the coupled maritime and economic networks, and how are they interconnected?

Chapter 4 proposed a systemic risk framework for different networks interconnected through ports, including the local port and critical infrastructure network, the regional hinterland transport network, the global maritime transport network, and the economic supply-chain network. Moreover, Chapter 4 described state-of-the-art risk modelling approaches to quantify systemic risks, identified critical gaps in the literature, and proposed a risk layering framework to address systemic risks. The overview of the literature suggested that, often, risks to the various network elements and the way they can propagate across networks are not known or are not available in a way that allows decision-makers to make informed decisions how 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 enable a detailed risk analysis. In particular, large data gaps exist to study systemic risks on a regional or global scale. Some of the most critical gaps identified are the lack of modelled or observed freight flows for different maritime and hinterland transport network components (which are essential to quantify the implications of network failure), a limited understanding of how maritime trade flows are used in the economy, and a lack of information on the resilience embedded in the maritime transport system, in particular how this differs per port, country or economy sector. Overall, Chapter 4 proposed several ways to move from a traditional risk framework towards a systemic risk framework to quantify port and supply-chain risk, and evaluate the system-wide benefits of improving resilience.

8.1.3 What is the criticality of ports in international trade and global supply-chains?

Chapter 5 introduced a new global maritime transport model, the OxMarTrans model, that simulates the flow allocation of global (maritime) bilateral trade flows on the maritime and hinterland transport networks and through specific ports (for 1380 ports). These downscaled trade flows were embedded within a global supply-chain database to link port-level trade to economic activity. This new systems framework of the coupled maritime transport and economic networks therefore allowed the evaluation of the different dimensions of the criticality of individual ports in international trade, maritime transport and the global economy. Several key dependencies and feedbacks were identified. Globally, approximately 50% of global trade by value is via maritime transport, although some sectors, like mining and agriculture, are found to be much more dependent on maritime transport (>80%). Freight flows are highly concentrated in a small number of ports that benefit from economies of scale and are well-integrated with the maritime and hinterland transport networks; around 50 ports (out of the 1380 considered) are responsible for 50% of global maritime trade. Moreover, low income economies and small island developing nations depend disproportionally on their port infrastructure for trade. Low income countries import 1.5 times more by means of maritime transport than high-income countries, while SIDS economies depend twice as much on maritime imports compared to non-SIDS economies. There are large cross-border dependencies between ports and the economies they serve due to land connections or transhipment services, with transhipment services and the use of ports in foreign (land-connected) countries accounting for 35% of global port throughput. Several important cross-border links were identified, such as between landlocked countries in Africa and South America and specific coastal ports, and island economies in the Pacific and the Caribbean that rely on regional transhipment hubs. Port were further found to be essential to integrate domestic and global supply-chains. In relative terms, every USD flowing through a port is associated with 4.3 USD, on average, of economic activity. While some of the world's largest ports are found to be critical for the global economy (>1.4% of global output depends on trade going through these ports), a number of ports (40) in trade-dependent economies facilitate trade that is critical for >10% of domestic industry output. Finally, for every 1000 USD increase in final demand (e.g. domestic consumption and exports) in an economy, the ports serving that economy experience a median 85 USD increase in maritime imports, with some (27) individual ports importing over 100 USD per 1000 USD change in final demand in the economies they serve. This new modelling framework highlights the close ties between ports and the economy, underlining the need to integrate long-term planning of port infrastructure with a system-wide understanding of the interconnected transport and the economic system.

8.1.4 What are the present-day climate risks to global port infrastructure and the resulting logistics and trade losses?

Chapter 6 presented a new modelling framework to quantify the risks that ports face from multiple natural hazards on a global scale. To do this, an asset-level risk analysis of global port infrastructure from multiple hazards was performed, underpinned by the development of a new global port infrastructure database and the processing of various high-resolution hazard datasets. The results showed that the vast majority of ports (~86%) are exposed to more than three hazards (out of six) with expected risk from physical damage and logistics losses (i.e. port-specific risk) totalling 7.5 (4.0-17.5) USD billion per year on a global scale. Although the risk to port terminals contributes most to this port-specific risk, the infrastructure that connects to ports (e.g. roads, rail, electricity) is also an important source of vulnerability, especially in high-income countries. In addition to this port-specific risk, 63.1 USD billion of trade (or 0.8% of maritime trade worldwide) is at risk every year from port disruptions induced by natural hazards. This trade risk is particularly high for small island nations. Both the port-specific risk and trade risk estimates are, however, sensitive to parameters that determine a port's resilience. The critical factors that determine resilience vary significantly across ports. Whilst some ports would benefit from strengthened construction standards, others are sensitive to the conditions that determine whether ships and ports can continue to operate (e.g. waves, wind speed). Altogether, this study present new risk estimates on a global scale, which is essential information for various stakeholders in the maritime sector, and highlights the need for investments to improve port resilience provided that the risks that ports face are expected to increase in the future as a result of climate change, the projected increase in maritime trade flows, and the ongoing expansion of port areas.

8.1.5 What are the future climate risks to port infrastructure and trade as a result of climate change and the need for new port expansions, and how does this affect the design and planning of new port expansions?

Chapter 7 explored the future climate risks (i.e. physical damages and revenue losses) and planning uncertainties to existing ports and new port expansions as a result of climate change and the evolution of trade (for 2050). To do this, 14 future trade scenarios, that vary according to the degree trade liberalisation, socio-economic growth and climate mitigation, were fed into an engineering-based port planning model to project the need for new port expansions. These port area projections (and the associated investment needs) were combined with modelled climate risks to these ports, creating a risk profile of the future climate risks these ports face. The results showed that an additional 1353 - 5735 km^2 of port terminals will be needed, requiring 1.3 - 5.6 USD trillion of investments, with a large investment gap identified in low and lower middle income countries. The climate risks to ports will grow from 6.5 USD billion per year at present to 16.0 - 37.4 USD billion per year in 2050, due to climate change (dominant for ~50% of ports) and increased trade and infrastructure exposure (dominant for ~50% of ports). The largest planning uncertainties, due to climate and trade uncertainty, were identified for ports located in parts of Sub-Saharan Africa, India and South-East Asia, which are also areas with some of the largest port infrastructure investment needs. This poses significant financial risks to these investments. Ports with rapid expected growth and relatively low relative climate risk (compared to the investment needs) have the opportunity to design new port infrastructure to be adapted to climate change at relatively low cost (compared to the cost of subsequent retrofit). Ports that have this potential are found in Sub-Saharan Africa, Indonesia and parts of South and East Asian. On the contrary, some ports in Japan, Western Europe and North America have little expected growth and large relative climate risk, which are areas where expansive retrofits are likely inevitable. Chapter 7 calls for a new decision-making framework, which incorporates flexibility into port planning and design through incremental developments, designing for future retrofit, and timely review when new information becomes available.

8.2 Discussion

Several cross-chapter points for reflection have been identified and are discussed below. These points are by no means all-encompassing, but merely reflect some of the most frequently recurring topics discussed across the chapters and during discussions with various organisations and stakeholders.

8.3 Different challenges faced across ports

The global comparison of ports showed that challenges faced by ports across geographies are unique and driven by the local context. Although generalised conclusions should be taken with caution, several overarching challenges and opportunities are identified.

Ports serving small island developing nations are small in size, often have deteriorating or aging infrastructure, are inefficient, and experience difficulties in terms of providing year-round operations. On top of that, these ports often have a low maritime connectivity and are critically dependent on certain maritime transport routes (often through one or two transhipment hubs) (Chapter 5). Nonetheless, they are found to be among the most vital for the respective economies they serve, often facilitating trade that is critical for over 10% of the national industry output and consumption (Chapter 5). However, these ports face some of the highest risk in terms of expected annual downtime (Chapter 6). Hence, despite not showing up in the various absolute risk metrics, in relative terms they are risk hotspots given the potential consequences of port disruptions for the economies they serve and the limited resilience embedded within the maritime logistics services that support these island nations. Investments in climate-proofing and upgrading the aging port infrastructure are essential to prevent more frequent downtime, alongside making sure economies are able to cope with potential trade bottlenecks. In particular, for these economies, a regional perspective on (systemic) resilience is required given the large negative spill-overs of disasters, but positive spill-overs of strategic adaptation (e.g. strengthening of transhipment hubs).

Large ports in developed (upper middle income or high income) economies face the highest absolute risk, given the vast size of port areas, the high density of (valuable) infrastructure, and the large concentration of global trade flowing through these ports (Chapter 6). In relative terms, however, they face much lower climate risk given the highly elevated decks of modern terminals and existing flood protection levels. Despite, this, some of these ports are expected to experience limited future growth in throughput, while climate change is elevating the climate risk these ports face (Chapter 7). This will likely result in the need for expensive retrofits of vast amounts of port infrastructure. In cases where this might be technically difficult or prohibitively expensive, alternative resilience strategies on a system-level have to be considered such as diversifying trade flows through different ports and transport routes that are less hazard exposed, or adding flexibility in terms of rerouting options (e.g. by adding sufficient spare capacity in alternative ports).

Ports in low and lower-middle income countries are generally small or moderately large, and either very specialised ports (e.g. mining exports) or act as regional hubs, such as container ports in sub-Saharan Africa that serve the African landlocked countries (Chapter 5). Low-income economies often disproportionally rely on maritime transport for international trade. Nonetheless, they have, generally speaking, low absolute and relative risk at present due to smaller port areas and lower hazard exposure (despite lower protection levels) (Chapter 6). While having a favourable risk profile at present, they will experience the fastest growth in climate risk as a result of climate change and, more importantly, growth in future trade (Chapter 7). The growth in trade in absolute terms means that large investments have to be made in developing new port infrastructure over the decades to come, with a large share of these investments coming from the private sector (given that investments of up to 0.5 - 2% of GDP are needed). However, the expansion needs are very much dependent on the trade and climate scenario, resulting in large financial risks to these investments, in particular in Sub-Saharan Africa, South Asia and India (Chapter 7). On the other hand, the combination of large investment needs and the relatively small climate risk provides a window of opportunity to mainstream adaptation into investments decisions at relatively low cost for many of the ports (Chapter 7), which requires proactive port planning that incorporates future climate risk in design.

8.3.1 The importance of providing multi-hazard risk information

Most of the existing literature has focused on performing risk analyses to ports considering a single hazard or a small subset of hazards. While the hazard of choice likely reflects the local context in terms of the most threatening hazard for a specific port, it makes it hard to generalise the results and provide an understanding of the relative importance of the various hazards that could affect a port. Similarly, there has been a divide between research intending to quantify the operational downtime of ports, which are often high-probability but low-impact events, and the physical asset damages due to the occurrence of natural disasters, which are low-probability but high-impact events.

As Chapter 6 identified, 86% of ports are exposed to more than three hazards (out of six considered), which include both natural disasters and marine extremes that exceed operational thresholds. Therefore, reconciling the two in one overarching risk framework helps in comparing and contrasting the relative importance of these hazards. For instance, the quantification of the port-specific risk in Chapter 6 showed that natural disaster occurrence often dominates the risk metric, although for some 22% of ports the logistics losses, driven mainly by operational disruptions, dominate the risk metric. As dealing with operational disruptions and physical asset damages involves different resilience strategies, such an overarching risk framework helps in identifying a portfolio of suitable resilience options.

The same holds for the future changes in climate risk. While most of the existing risk studies have considered sea-level rise as a main driver of future climate risk, results in Chapter 7 highlighted that it is often a combination of hazards that together change the future climate risk profile of a port. Providing medium and long-term projections of climate risk, disaggregated per hazard type, could help inform port authorities and other organisations in terms of the expected change in risk. As the UNCTAD (2017) survey on port adaptation practises demonstrated, port authorities often lack long-term scenarios of most climate variables (apart from sea-level rise). Although the climate risk indicators presented in this thesis are by no means a substitute for regional or local analysis of changing climate risk for specific ports, the information provided in this thesis can be a valuable starting point for many port authorities that lack the capacity and budget to perform such detailed hazard modelling and risk analysis.

8.3.2 Moving from coarse exposure analysis to asset-level risk analysis enables monetising risk but comes at the expense of large uncertainties

Previous risk analyses faced various data and modelling constraints that prevented them from scaling up local risk assessment to a regional or global scale. As a result, previous large-scale risk analyses simplified ports areas as single point locations, and often only focused on the exposure of ports (that is, they did not consider nor quantify the impact mechanisms for damages and losses). The risk framework presented in Chapter 6 demonstrated how representing ports as a set of (geospatial) infrastructure assets (e.g. cranes, terminals, warehouses, breakwaters), and by explicitly capturing physical damage mechanisms and operational downtime (through fragility and reconstruction curves), the risk in terms of physical asset damages and operational downtime could be monetised. This was only feasible by constructing a new global database of ports infrastructure assets. Similarly, by modelling the present-day and future trade flows going through individual ports (Chapter 5 and Chapter 7), the risk of operational downtime could be translated into trade and logistics losses, something that was hitherto not considered on a large scale. These extensions provided the basis for a global comparative framework in which hotspots of risk could be identified at present and in the future.

However, performing such an integrated risk analysis comes at the expense of having to make a large number of assumptions and generalisations. The sensitivity analysis performed in Chapter 6, by varying 45 model parameters, illustrated that uncertainties can quickly accrue through the risk analysis and may vary depending on the risk metric adopted. However, what Chapter 6 also showed is that performing sensitivity analysis could provide useable insights in the critical parameters that drive the resilience of different ports. The critical sensitivities identified per port could not only help specify which parameters should be better parametrised when performing a regional or local risk analysis, but also how an improvement (adaptation) or deterioration (lack of maintenance) of certain critical parameters (e.g. engineering standards, operational thresholds) could change the risk metrics.

8.3.3 Critical infrastructure networks converging in ports are an important source of operational vulnerability

Operational disruptions at ports do not solely occur because of direct impacts to port infrastructure, but could also occur if critical infrastructure (e.g. roads, railway, electricity) in the direct vicinity of ports, or located in the port hinterland, are affected by climatic extremes (Chapter 4). For instance, the climate risk analysis performed (Chapter 6) showcased how transport and electricity networks in direct vicinity of the ports (1 km) could result in substantial risks to port operations, in particular for ports located in Western Europe and North America. Similarly, in Chapter 3, several past disruptive events where identified in which disruptions to transport infrastructure that connect hinterlands to their respective ports caused a significant loss in operations (in particular flooding of railways lines and low flows affecting inland water transport). These hinterland criticalities are particularly relevant for the transport of low-value bulky goods, such as agricultural or mining goods, that can often only cost-efficiently be transported on a specific mode or route.

Hence, risk analysis should be extended from a port-centric view towards a port-hinterland transport view, as discussed in Chapter 4. Extending the scope towards port-hinterland transport corridors also requires an integrated approach to address the identified risks, as the ownership and responsibilities of port assets and hinterland transport assets differ between the two (often public versus private), as well as engineering standards adopted (e.g. flood protection standards). Despite some port authorities recognising this issue, this is not been translated into research that quantifies the climate risks to port-hinterland transport corridors. The transportation model developed in Chapter 5, which includes a simplified representation of the flows on the hinterland transport network, could be used as the starting point for such an analysis, in which the criticality of a certain hinterland transport network (e.g. in terms of freight flow) is combined with the likelihood of climatic extremes occurring along these routes.

8.3.4 Systemic risks cannot be neglected and should be managed

Systemic risks, referring to indirect economic losses as a result of a single port disruption, are inherent to the interconnected nature of the global maritime transport and economic system. The systemic risks to various actors (port authorities, carriers, shippers, firms), which are a combination of public and private losses, can be very large, potentially exceeding the physical asset damages. For instance, in Chapter 6, the logistics losses were defined as the revenue losses to port terminal operators, carriers and shippers as a result of port downtime. At present, these logistics losses equate to around one third of the annual expected physical damages to port infrastructure assets, although are the dominate risk driver for around 22% of ports.

More importantly, every year, around 0.5% of global port throughput is at risk of being disrupted (Chapter 7), with the value of this throughput being over ten times larger than the physical asset damages. As was shown in Chapter 5, every dollar of maritime trade lost could cause around 4.3 USD loss in industry output through supply-chain interdependencies. In other words, every year, industry output worth ~0.5% of global GDP is at risk of facing disruptions due to the climate-induced port downtime. For some economies the amount of economic activity exposed can be much higher, since 40 ports were identified to serve over 10% of a country's domestic industry output (Chapter 5). Therefore, systemic risks in absolute terms can have implications that are globally significant, while in relative terms systemic risks are most threatening for small island nations given that their economic activity is often reliant on a single port. Chapter 7 further found that the change in trade risk is not changing much in relative terms, increasing to 0.6 – 0.7% in 2050, but will expose significantly more trade every year given a 100 to 300% growth in global throughput by 2050.

How the trade and economic activity at risk translates into actual economic losses depends critically on the level of resilience at the port-level, and within maritime transport and supply-chain networks. Although not explicitly quantified in this thesis, several reflections on this can be made. First, a large share of this trade or economic activity will not be lost, but merely delayed for a short amount of time (i.e. order of days). Chapter 3 showed that ports are often able to (partly) recapture delayed trade flows by temporarily ramping up production. Second, as discussed in Chapter 3, mixed evidence of the ability to reroute goods was found, due to various technical and operational constraints. As highlighted in Chapter 5, given the large concentration of flows on specific routes, through a small subset of ports (around 4% of ports handle 50% of global throughput), or dependent on a specific transhipment hub, longer-term disruptions to specific critical nodes in the network will inevitably spill over to national or foreign supply-chains, as was clearly illustrated during the 2021 Suez Blockage and the 2022 closure of Ukrainian ports as a result of the war. For these types of disruptions, the resilience of firms, and supply-chain network as a whole, becomes critical. While most firms will have inventories to cope with short delays, alternative resilience options have to be considered for longer-term disruptions. Although existing research suggest that macroeconomic losses can be reduced significantly based on the existing resilience measures embedded in the economic system, this evidence is entirely based on case-studies of port disruptions in the United States and by no means representative of other economies.

Altogether, the different actors involved in the maritime and economic system that depend on ports should implement risk management practises to cope with systemic risks by considering low-probability but high-impact events (e.g. stress-tests) alongside the high-probability but low-impact events that are (often) already considered. A system-wide representation of the interconnected system, as presented in this thesis, could be the basis for that.

8.3.5 The need for adaptation for existing and new port expansions

As Chapter 7 underlined, climate change alone will elevate the climate risks to ports by a factor 1.7 - 2.2 at the mid-century, depending on the climate scenario adopted. In other words, irrespective of the decarbonisation pathway taken over the next 30 years, adaptation in ports is required to maintain or lower current risk levels. Depending on the risk profile of a port, adaptation options could include strategies that help prevent the occurrence of negative impacts to assets and operations (e.g. upgrading drainage, elevating terminals or breakwaters), resist its impacts (e.g. improve engineering standards), or speed up recovery (e.g. using emergency response plans). The sensitivity analysis in Chapter 6 showcased that port-specific risk is most efficiently reduced by improving engineering standards (e.g. design codes, upgrading drainage), while for a certain number of ports improving operational thresholds (e.g. tug boats that cope with higher waves, cranes that can operate at higher wind speeds) was found to be the most beneficial option. For trade risk as a result of downtime, however, the most suitable adaptation options vary widely across ports with cyclone-prone regions benefitting from improved engineering standards, ports in Europe, Japan and North America benefitting from improved operational standards, while ports in South-East Asia, northern Europe and northern China benefitting most from improved recovery efforts.

The combined effect of climate change and port expansions was found to further amplify the climate risk to ports, increasing risk by a factor 2.4 – 5.8 depending on the trade and climate change scenario (Chapter 7). For around half the ports globally, the need for port expansions (resulting in more infrastructure and trade at risk) dominates the increase in risk, making it imperative that climate change adaptation is incorporated in new expansion projects. As most socio-economic scenarios suggest that population and GDP will level off after 2060, global trade flows are similarly expected to slow down or stagnate after 2060. In other words, most of the new port expansions to meet demand for the 21st century are likely happening over the next 30 years, and are thus already being planned at present or will shortly be put on the agenda (given the long planning horizons). As Chapter 7 outlined, ports in Western Africa, Sri Lanka, Eastern Europe and parts of China have the potential to mainstream adaptation into new port investments at low additional costs, given the relatively low climate risk and large expansions needs. If adaptation is not mainstreamed into new expansions, retrofitting port infrastructure afterwards would be required, which is perceived to be prohibitively expensive, technically challenging, and would require shutting down (part of) the port operations, incurring significant revenue losses.

In other words, given that trade demand will likely peak over the next 30 – 40 years, but the lifetime of infrastructure is around 80 - 100 years, there is a trade-off between taking pro-active action now, incurring higher upfront costs, or waiting longer with the risk of having to do costly retrofits. Suitable risk evaluation frameworks, that explicitly deal with large uncertainties, are needed to justify either of these decisions, something that is hardly considered in the literature. However, such alternative paradigms that better deal with uncertainties in port planning have recently been proposed by port authorities. For instance, the Adaptative Port Planning approach, adopted by the Port of Rotterdam, emphasises the need for flexibility and robustness in infrastructure investment decisions given large future uncertainties (Taneja, Ligteringen and Walker, 2011).

8.4 Recommendations for future research

Several opportunities exist to improve and extend the research presented in this thesis. A number of high priority future research directions are highlighted below.

8.4.1 Information on port-level resilience

Extending risk analysis from a local to a global scale involved making many assumptions and generalisations, such as assuming that ports have similar operational thresholds, engineering standards, adaptation practises and resilience. Some of the existing surveys on ports' susceptibility to climate hazards has shown that critical thresholds differ considerably per port. Therefore, constructing new databases that include how some of these resilience parameters differ across ports, and whether this can be linked to country characteristics, the size of ports, or cargo specialisation can help improve the risk estimates presented in this thesis.

8.4.2 Evaluate the existing resilience in the maritime transport network

Evidence presented in this thesis has outlined that there is already some level of resilience at the port-level and within the maritime transport network. However, it is unclear whether this is a general observation or not, and to what extent it depends on the type of commodity, duration of the disruption, spare capacity embedded in substitute ports, or other technical or logistics factors (e.g. hinterland connections, draft limitations). Extending the knowledge base on system-wide resilience, using a combination of surveys/interviews with actors involved in the logistics chain as well as modelling approaches, could help bridge this knowledge gap and incorporate this type of information into the risk analyses.

8.4.3 Single versus simultaneous port disruptions

In this thesis, risk is quantified on a port-by-port and hazard-by-hazard basis, after which the individual risk numbers are aggregated to derive global risk numbers. However, to quantify systemic risks, the likelihood of multiple ports being simultaneously disrupted needs to be considered. In Chapter 3, it was shown that in reality multiple ports are often affected during a single event, in particular as a result of tropical cyclones, underlining the importance of including this. This is not only critical for the magnitude of the resulting losses, but also for the ability of the system to cope with disruptions, as otherwise substitution ports might also be affected. Similarly, compound hazard events are not considered in this thesis, which could amplify the physical damages and downtime of ports if impacting different port infrastructure simultaneously (e.g. extreme wind damaging cranes alongside flooding of terminals and critical infrastructure). Hence, moving from a port-by-port risk perspective towards an event-based risk perspective can help move this research agenda forwards.

8.4.4 Quantifying global economic impacts

While the link between maritime trade and global supply-chains has been evaluated in this thesis (Chapter 5), which allowed quantifying the economic activity (production and consumption) at risk of being disrupted, the macroeconomic losses associated with this are not considered. Extending the present modelling framework by including a macroeconomic impact model can help evaluate which fraction of the economic activity at risk is being actually lost. This could help quantify how this differs across hazard events and ports, and where and which additional resilience measures are most beneficial from a macroeconomic perspective.

8.4.5 The cost and benefits of mainstreaming adaptation in infrastructure investments

As mentioned in this thesis, there is a large opportunity to mainstream adaptation into new investment decisions, such as infrastructure upgrades or new port expansions. However, despite some literature quantifying the costs of upgrading existing infrastructure, the cost and benefits of incorporating adaptation in new infrastructure remains unexplored. This should be supported by a decision analysis framework that captures the benefits of adaptation (compared to the baseline of not adapting) and the associated cost given the type or degree of adaptation implemented. Given the long lifespan of infrastructure, this type of analysis should a stress-testing exercise to evaluate whether adaptation decisions are robust given a large variety of uncertain future scenarios and other critical factors for that determine the success of the investments (e.g. future trade, climate change, service lifetime). Local studies can provide context specific evidence that could be ultimately be scaled up globally to quantify the amount of adaptation finance that needs to be mobilised.

8.5 Towards pro-active risk management

Over the last few decades, the maritime sector has experienced considerable growth, with an increasing concentration of trade flowing along major transport corridors and through a small subset of large hub ports. As a result, ports and countries have become increasingly interconnected with each other, contributing to supply-chain integration, economic development and poverty reduction. Within this same time frame, only a relatively small number of large-scale disasters have caused major port disruptions with severe global repercussions (e.g. Hurricane Katrina, Tohoku Earthquake, Typhoon Maemi), alongside recurring small-scale operational disruptions that are often planned for and easy to cope with.

However, as this thesis stresses, the time of smooth sailing might soon be over. Port authorities, and the maritime sector as a whole, need to urgently shift their risk management practises to one in which the occurrence of low-probability but high-impact events, which are often not planned for, are becoming increasingly likely. Recent disruptive events, such as the 2021 Suez Blockage, the COVID-19 pandemic (resulting in spikes in freight rates and bottlenecks at ports across the world), the 2020 explosion in the port of Beirut (which cut off Lebanon from its essential imports), and the Russia-Ukraine war (closing all Ukraine ports and threatening global grain supplies) have showcased that disruptions to the maritime transport network can have large knock-on effects that are felt across the world. While, at present, the maritime logistic system is designed to meet demand across the globe in the most time- and cost-efficient manner, this has come at expense of having limited resilience against large shocks that disrupt critical nodes in the network.

Hence, port authorities and other maritime actors are at a crossroads. A continued focus on maximising short-term benefits and limited attention for climate change adaptation will inevitably overwhelm parts of the system as early as 2050, with ports in small island developing states expected to be at the forefront of this. On the other hand, pro-actively including climate change in infrastructure expansions and upgrades have the potential to cost-efficiently adapt to climate change and create large positive externalities to other ports and economies. Some ports, mostly in developed countries, are proving to be frontrunners, by performing climate risk analysis and implementing adaptation into planning and design, while others lack the necessary data, technical capacity and financial resources to do this. Therefore, location specific climate risk information, as presented in the thesis, can be the starting point for port authorities, or those financing new port expansions and adaptation measures (e.g. multilateral development banks), to address climate change in tandem with achieving operational and financial targets.

However, residual risks will remain, in particular in terms of systemic risks that cannot be addressed by a single port alone. As reiterated throughout this thesis, to build resilience in the interconnected maritime and economic system, systemic risks have to be quantified to identify critical network components, anticipate the impacts, and identify suitable resilience options to reduce risk. This requires a holistic approach on both a local and global scale, and an unprecedented collaboration between all actors involved within the maritime logistics and economic supply-chain. As such, this thesis provides a blueprint for this shift in thinking, which will ultimately help safeguard the sustainability of port operations, maritime transport and economic development in the near and distant future.

9 References

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10 APPENDICES

APPENDIX 1 AUTHOR CONTRIBUTIONS AND STATEMENTS

To specify the contributions of all authors in the respective chapters (and papers), the CRediT (Contributor Roles Taxonomy) taxonomy is adopted. Credit was introduced to recognise individual author contributions. An author is assigned one or more of the options (out of 14 options) as specified in Supplementary Table A1.1.

Supplementary Table A1.1: Overview of the terms and definitions as per CRediT taxonomy

Term	Definition
Conceptualization	Ideas; formulation or evolution of overarching research goals and aims
Methodology	Development or design of methodology; creation of models
Software	Programming, software development; designing computer programs; implementation of the computer code and supporting algorithms; testing of existing code components
Validation	Verification, whether as a part of the activity or separate, of the overall replication/ reproducibility of results/experiments and other research outputs
Formal analysis	Application of statistical, mathematical, computational, or other formal techniques to analyze or synthesize study data
Investigation	Conducting a research and investigation process, specifically performing the experiments, or data/evidence collection
Resources	Provision of study materials, reagents, materials, patients, laboratory samples, animals, instrumentation, computing resources, or other analysis tools
Data Curation	Management activities to annotate (produce metadata), scrub data and maintain research data (including software code, where it is necessary for interpreting the data itself) for initial use and later reuse
Writing - Original Draft	Preparation, creation and/or presentation of the published work, specifically writing the initial draft (including substantive translation)
Writing - Review & Editing	Preparation, creation and/or presentation of the published work by those from the original research group, specifically critical review, commentary or revision – including pre-or postpublication stages
Visualization	Preparation, creation and/or presentation of the published work, specifically visualization/ data presentation
Supervision	Oversight and leadership responsibility for the research activity planning and execution, including mentorship external to the core team
Project administration	Management and coordination responsibility for the research activity planning and execution
Funding acquisition	Acquisition of the financial support for the project leading to this publication

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- Verschuur, Koks and Hall (2022), Port's criticality in international trade and global supply-chains, *Nature Communications*, *13 (4351)*
- Verschuur, Koks, Li and Hall, Multi-hazard risk to global port infrastructure and resulting trade and logistics losses, *under review in Communications Earth and Environment*
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APPENDIX 2: SUPPLEMENTARY INFORMATION 'PORT'S CRITICALITY IN INTERNATIONAL TRADE AND GLOBAL SUPPLY-CHAINS'

Contains:

Supplementary Note A2.1-3

Supplementary Figure A2.1-11

Supplementary Table A2.1-7

Supplementary Note A2.1: Modal split model

We develop a global modal split (or modal choice) model to predict the share of maritime trade in every bilateral trade flow. A model split model intends to predict the allocation of freight transport flows for a given Origin-Destination (O-D) pair provided with alternative and competing transport modes (de Jong, 2013). We fit the model based on reported modal share data of international trade from UN Comtrade (United Nations Statistical Division, 2020), which includes reported modal split for around 50 countries that report this data. Afterwards, we predict the model split in every bilateral trade flow reported in the harmonized BACI trade database (Gaulier and Zignago, 2010), which the most comprehensive database of historical trade flows. We use 2015 as our base year as it is the latest available year (at the time of writing) available in the EORA MRIO database.

We consider maritime, air and land (road and rail) transport as alternative transport modes, given nearly all trade in our sample is by means of these three modes. We adopt a multinomial logit formulation, as is common practise into transport modelling (Ben-Akiva and Bierlaire, 1999; Ben-Akiva and de Jong, 2008; de Jong, 2013), which is based on the concept of utility maximisation given a set of alternative modes, which have mode-specific variables (e.g. distance, time), as well as characteristics of importing and exporting country (e.g. income level, island, neighbouring countries), and the commodity (e.g. quantity, value to weight ratio, perishable or not). Utility here captures how a decision-maker, in this the case the shipper of the good, values the use of a transport mode to ship goods, with the shipper seeking to maximize the utility across the transport modes available to them (Ben-Akiva and Bierlaire, 1999). The model is set up to predict the share of maritime trade given the availability of maritime, air and (if possible) land transport.

In general, one can write the utility of a given mode (m) for commodity (c) as:

$$U_{m,c} = \beta_1 C_m + \beta_2 t_m + \beta_i U_m + \beta_i V_c + M_m$$

With *C* being the transport costs (USD per tonnes), *t* being the transit time (hours), *U* being a set of explanatory variables of the country pairs but irrespective of the commodity (GDP per capita of origin and destination, neighbouring country dummy, island dummy), *V* being a set of explanatory variables related to the commodity being shipped (quantity, value per tonnes, perishable dummy), and *M* being a mode-specific constant.

The cost function we adopt includes both the distance costs and the time costs, which was found to be the best performing formulation in previous work (de Jong *et al.*, 2010). The total costs per mode (*C*) can be written as:

$$C_m = D_{c,m} d_m + T_{c,m} t_m + H_{c,m}$$

With D_c being the distance costs (USD per tonnes-km), *d* the distance (km), T_c the time costs (USD per tonnes-hour), H_c the handling costs (USD per tonnes), and *t* the transit time (hours). The time component is added in the cost function as well as a separate variable (β_2), which reflects that changes in the transit time not only results in capital costs, but also other value of time costs related to depreciation, inflation and insurance (de Jong *et al.*, 2010). For some commodities, this can be an important additional factor to decide upon a certain transport mode (e.g. for time sensitive goods).

Per origin and destination flow, and per commodity, the share per mode (*S*) can be estimated using the multinomial mode choice probability (Ben-Akiva, Bolduc and Park, 2008):

$$S_{m,c} = \frac{e^{U_{m,c}}}{\sum_{j \in m} e^{U_{j,c}}}$$

With *m* the number of mode alternatives, which is three for country pairs where land transport is available and two for country pairs where this is not.

Observed modal share data is collected from UN Comtrade (United Nations Statistical Division, 2020) for the period 2016-2018, which, for the countries that report this, describes per bilateral trade flow on a commodity level (HS6). the share of different modes of transport being used. We filter out trade flows between non-landlocked countries in order to avoid misclassification of the mode of transport (e.g. Switzerland reports trade from Argentina as being road, because it uses road transport to enter the country) and remove trade flows that are specified as road, but where no road connection is present (e.g. trade from Brazil through the Port of Rotterdam to Germany is classified as road or rail). This results in 6.8 million bilateral trade flows between ~12,000 unique country pairs.

To fit the modal split model, mode-, country- and commodity-specific data was collected. For the country-specific data, we use GDP per capita from the World Development Indicators database (World Bank, 2020b), neighbouring country dummies based on the

GeoDist database (Mayer and Zignago, 2011), and island country dummies, which are found by extracting countries without any neighbouring countries in the Geodist dataset. Commodity-specific data (on HS6 level) is collected from the BACI trade database (Gaulier and Zignago, 2010), from which we extract the total quantity of trade flows and the value to weight conversion. Perishable product dummies are taken from the database provided by Hummels and Schaur (Hummels and Schaur, 2013).

Mode-specific data per country pair includes the aggregated cost and time required to ship goods between both countries. To derive this, we create a global transport network for air, maritime and land-based transport modes. Per transport mode, we add information on the distance, speed, handling cost, and additional dwell times (e.g. loading and unloading time and dwell time at port, airport, land border) to the network. As origin and destination locations, we use the centroid of countries derived in earlier work (Hall *et al.*, 2019), in which nightlight data was used as a suitable weight to create country centroids.

For land-based transport, a global road transport network is extracted from the gROADSv1 global road database (Center for International Earth Science Information Network - CIESIN - Columbia University and Information Technology Outreach Services - ITOS - University of Georgia, 2013), while for the rail transport network OpenStreetMap (OSM) railway data is used. For both networks, we create a routable unidirectional network connecting the road/rail segments. At the borders, a border crossing time is added, which resembles border compliance processes (e.g. customs, etc). Border compliance time per country is taken from the World Bank's Doing Business database (World Bank, 2020a), which is added to every border crossing between two countries by taking the average of the two countries' border compliance time. For every road and rail segment, we add a speed proxy per country, for which we distinguish between two groups of countries in line with Martínez *et al.* (Martínez, Kauppila and Castaing, 2015) and which are summarised in Supplementary Table A2.3. Moreover, we add distance and time costs to every segments, as well as handling costs and loading/unloading times at nodes where goods are transhipped from one mode to the other (e.g. centroid to road, road to rail, etc). The distance costs are taken from a database of mode specific distance costs for country globally provided by the ITF-OECD (Martínez, Kauppila and Castaing, 2015). Time costs, handling costs and (un)loading times are taken from the literature and included in Supplementary Table A2.4-7. We run lowest cost paths between all centroids using Dijkstra shortest path algorithm (Dijkstra, 1959), and derive the time associated with the lowest cost route. If both road and rail connections are feasible, we use the lowest cost of both modes as the representative land-based shipping costs.

For air transport, we create a global network of flight connections between airports. To do this, we combine data on passenger flight connections from OpenFlight database (https://openflights.org/data.html) and a global air cargo network (based on data of four major air cargo freight integrators) (Bombelli, Santos and Tavasszy, 2020). We connect country centroids to the airports via the road transport network, and add a dwell time at the airports (time that goods spend at an airport) and a transhipment dwell time (in case there is no direct flight connection), which are set based on recommended values in previous research (Martínez, Kauppila and Castaing, 2015; Meijs, 2017). All parameters adopted are summarised in Supplementary Table A2.4-5. Moreover, we add distance, time and handling costs to the network (see Supplementary Table A2.5-7), after which estimate the cost and transit time per country pair using the shortest path algorithm.

To estimate the maritime transport costs and times, we create a maritime transport network based on Oak Ridge National Laboratory maritime transport network[1], which we connect to a set of 1450 ports globally (see Supplementary Note A2.3) and consequently to the road transport network. In addition, we create a database of ports that are connected to one another based on observed port visits from ship movement data (Automatic Identification System, AIS) for the period 2019 – 2020 (see Supplementary Note A2.3). Hence, flows can only happen between ports that are connected to each other in the transport network. Several dwell times are added to this network. First, if a port in a neighbouring country is used, the border cross time is added in line with the land transport network. Second, at every port, we add a turnaround time of vessels based on the median turnaround time derived from AIS data over the period 2019 – 2020. Third, we add a cargo dwell time and transhipment dwell time to the ports, which are based on previous work (Martínez, Kauppila and Castaing, 2015) and summarised in Supplementary Table A2.5. After adding distance, time and handling costs to the network, we derive the maritime shipping costs and time per country pair (see Supplementary Tables 5-7).

We fit a separate modal split model for the 11 sectors adopted in this work to capture sector-specific model parameters. We perform a validation of the data on a sector level, with scatterplots included in Supplementary Figure A2.10. For the maritime modal share, the regression models have a R-squared values ranging between 0.36 – 0.52, while the final maritime trade validation yields R-squared values ranging between 0.41 – 0.99.

[1] https://tedb.ornl.gov

To create a harmonized maritime trade dataset, we fit the model with the entire 2015 BACI harmonized trade dataset (Gaulier and Zignago, 2010), which comprises commodity-specific (HS6) trade data on 8 million bilateral trade flows between ~24,000 unique country pairs. We use the 2015 trade data for this prediction given that we couple this data to the EORA MRIO table, which has 2015 as its most recent year. As additional validation, compare the predicted maritime shares for the United States, Australia, New Zealand and Europe to reported numbers, which show an overall good result (Supplementary Note A2.2).

Supplementary Note A2.2: Validation modal split model

Apart from the internal validation process, we perform an external validation of the results for countries for which we could find modal share data. For New Zealand, we find that maritime transport accounted for 81.4% of imports and 90.9% of exports in 2015, whereas the official data (average of 2005-2015)[2] showed that these shares were 77% and 88%, respectively. In Australia, 84.5%[3] of all trade by value is maritime, which is in line with our prediction of 82.2% of trade in terms of value. For the United States, we find maritime import and export shares of 55.3% and 51.5%, respectively, which are in line with the number provided by the United States Department of Transportation who estimated these

[2] http://archive.stats.govt.nz/browse_for_stats/industry_sectors/imports_and_exports/overseas-merchandise-trade/Methods-transporting-imported-and-exported-goods.aspx#gsc.tab=0

[3] https://shippingaustralia.com.au/wp-content/uploads/2020/11/SAL20048-FACT-SHEET-ON-AUSTRALIAN-TRADE-by-SAL-1.pdf

shares to be 53% and 38% in 2011[4]. The overestimation of exports can be caused by the different reference years used. Moreover, we underestimation the amount of land transport between the U.S.A. and Canada and Mexico, which is likely due to relatively large distance between the centroids of these countries. For the European Union (EU) countries, the share of maritime transport in extra-EU trade was 53.0% for imports and 48.1% for exports in 2015[5]. Our model prediction estimates these shares to be 45.4% for imports and 45.6% for exports in 2015. Our models overestimates the amount of goods entering Europe by means of land transport, particularly from Asia, where additional factors cause shippers to favour maritime transport over land-based transport. Moreover, we can estimate the accuracy per country for the EU28 countries. The prediction is well, with correlation coefficients of 0.77 (exports) and 0.65 (imports).

Supplementary Note A2.3: OxMarTrans model

This Supplementary Note describes the development of the new global maritime transport model, the OxMarTrans model, which simulates the allocation of maritime trade flows between subnational units globally on the maritime transport network. Previous research have made significant progress in developing global maritime transport models. Most notably are those developed by Tavasszy *et al*. (Tavasszy *et al.*, 2011), who constructed a network flow model to predict container flows between 437 container ports globally (with no explicitly hinterland representation), and Martinez *et al.* (Martínez, Kauppila and

[4] https://www.bts.gov/archive/publications/by_the_numbers/maritime_trade_and_transportation/index
[5] https://ec.europa.eu/eurostat/statistics explained/index.php/International_trade_in_goods_by_mode_of_transport

Castaing, 2015), who created a multi-modal transport model (which include the hinterland and maritime transport components) to simulate maritime freight flows (container, RoRo, bulk, liquid, general cargo) between 333 centroids globally. The OxMarTrans model is inspired by these previously developed models but includes several refinements and extensions; (1) we simulate flows between subnational units (3,380 centroids) instead of country centroids, (2) we include a simplified multi-model hinterland representation in the model, (3) we embed an observed maritime transport network, that consist of route connections between around 1400 ports globally, in the model to take revealed route choice decisions into consideration, (4) we add estimated sector-specific capacities to all ports and transportation routes, such that capacity constraints can be included in the model, and (5) we perform a sector-specific flow allocation (11 sectors) such that allocated flows can be linked to a multi-regional input-output table.

The model descriptions covers five components: (1) the origin-destination flow allocation, (2) the hinterland transport network representation, (3) the maritime transport network representation, (4) cost function, and (5) the flow allocation procedure. Moreover, we perform a validation of the model output.

Origin-destination flow allocation

Global country-to-country maritime trade flows, both in value and weight terms, per sector are derived from the global modal split model (see Supplementary Note A2.1: Modal Split Model). These flows will be routed on the hinterland and maritime transport networks between a number of origin (O) and destination (D) locations. Here, centroids of subnational administrative boundaries are taken as OD locations. We use administrative boundaries from the Database of Global Administrative Areas (GADM)[6], for which we extract the second administrative boundary layer per country, except for the United Kingdom for which we extract the third administrative boundaries. For countries without lower administrative boundaries (e.g. some small islands), we use the first administrative boundary layer. We use population data (CIESIN Gridded Population of the World, version 4[7] at 30 arcseconds) to assign a population weight to the centroids. We use the weight to determine the size of the trade flow between two regions. Similar as in Martinez *et al*. (Martínez, Kauppila and Castaing, 2015), Maritime trade flows (*F*) from administrative region (i) in the origin *(O)* and destination country *(D*) for a given sector *(s)* are found by scaling the total trade flow between the two countries with the admin population (*P*):

$$F_{O_i,D_j,s} = F_{O,D,s} * \frac{P_{O_i}}{P_O} * \frac{P_{D_j}}{P_D}$$

Per maritime trade flow between two centroids, the OD database contains information on the quantity (in tonnes) and value (in USD) shipped.

Hinterland transport network representation

The hinterland transport network consist of a multi-modal (road, rail, and inland waterways transport (IWW)) network representation that connects centroids to relevant ports. We do not aim to accurately simulate hinterland transport routes choices, but

[6] https://gadm.org
[7] https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-rev11

primarily aim to represent the integration of ports in the hinterland transport network and the availability of different modes to ship goods from port to centroid, as both aspects guide port choice decisions.

Centroids are connected to ports via the road, rail and IWW networks (if this option is feasible). We only connect centroids to domestic ports and ports in neighbouring countries, except for landlocked countries where we also connect centroids to ports in the neighbours of neighbouring countries. Centroids of island states are only connected to domestic ports, where we assume that a short-sea shipping network exist to import and export goods from smaller islands (in case an island nation consist of a number of smaller islands) to the main ports of the island states.

We use the global road and rail network, similar as described in Supplementary Note A2.1 to make the connections between admin regions and ports. For the IWW network, we extract global river network data from HydroRivers data[8] and the European IWW network from UNECE[9], and combine this with a global river port database from WorldPortSource[10]. Centroids are connected to river ports and railway nodes via the road network. We end up with a hinterland transport network that connects ~160,000 unique centroid-port pairs with one another.

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[8] https://www.hydrosheds.org/page/hydrorivers
[9] https://unece.org/where-navigate-network-inland-waterways-europe-and-its-parameters
[10] http://www.worldportsource.com/index.php

Maritime transport network representation

The maritime network consist of a network of ports and feasible maritime transport routes between port pairs. We have mapped the geographical location (lat/lon) of 1400 ports and derived information on the estimated turnaround time (time spend in port), the number of port calls, and port capacities per sector from Automatic Identification System (AIS) data in previous work (Verschuur, Koks and Hall, 2021a). Moreover, by analysing the sequence of port calls of around 10,000 vessels over time (between 2019 – 2020), we have derived a maritime transport database of connections between ports and the associated route capacity (based on the utilized capacities of the vessel). In total, the maritime transport database contains information on the distance and vessel capacity between ~150,000 port pairs in the global maritime transport network. To allocate this information on a routable network, we use the Oak Ridge National Laboratory shipping network, similar as in Supplementary Note A2.1, and link ports to the routable maritime network. The use of observed maritime transport information allows us to accurately simulate the port choice for trade between two country countries based on the integration (i.e. connectivity, capacity) of various ports in the maritime transport network. Moreover, it allows predicting transhipment flows between country pairs.

Different vessel types are being used to ship goods for the different sectors, which all have different costs, travel times, port capacities, unloading times, dwell time, and handling cost. Moreover, given that they use different terminals within ports, the transport networks do not necessarily interact with one another. Therefore, within the maritime network, we distinguish between five broad vessel types; Container, General Cargo, Liquid bulk, RoRo or Dry Bulk vessels. Based on an conversion table of vessel types to economic sectors derived in earlier work (Verschuur, Koks and Hall, 2021a), we can estimate what fraction of the capacity per vessel type is being used to ship goods for a certain sector. Therefore, the maritime transport database is also split between these five vessel types and the total maritime transport database contains information on ~280,000 port pair connections across the five vessel types.

At every port, a capacity is added per vessel type based on available AIS data. Port capacity is non-trivial, as many definitions exist (e.g. maximum instantaneous capacity, maximum annual capacity, optimum annual capacity), and there is no agreed standard definition, nor a global database, on port capacity. Here, we derive a globally consistent estimate of what we call the maximum operational capacity (MOC) of the port; the operational capacity which a port can theoretically reach within existing operational capabilities. First, per vessel type, we estimate the utilization rate (UR) of the port by looking at the weekly port capacity called at ports (multiply the number of calls with the deadweight tonnage of the vessels), and dividing the median with the maximum weekly port capacity called. We then estimate the yearly trade flow (TF) (incoming and outgoing flows) per port and vessel type using the methodology discussed in previous work using AIS data over the period 2019-2020 (Verschuur, Koks and Hall, 2021a). The TF is then divided by the UR rate to derive the MOC per port (p), vessel type (t) and flow direction (f):

$$MOC_{p,t,f} = \frac{TF_{p,t,f}}{UR_{p,t}}$$

Cost function

We add a freight cost to every network segment in our combined hinterland and maritime transport network. The cost function used is similar as the one used in Supplementary Note A2.1, except that we add an additional value of time in the cost function instead of estimating this separately as done in the Modal Split Model. The total freight cost (C) per mode (m) and sector (s):

$$C_{m,s} = D_{c,m}d_m + T_{c,m}t_m + H_{c,m} + \ VC\ VOT_s(t_m + L_m)$$

with *Dc* the distance costs (in dollar per tonnes per km), d the distance (km), *Vc* the value to tonnes conversion (USD per tonnes), Tc the time costs (in dollar per tonnes per km), *t* the transit time (in hours), VOT the value of time (in dollar per tonnes per hour), L the (un)loading and dwell time (in hours) and *Hc* the handling costs (in dollar per tonnes). The cost elements included capture the different components that together determine freight costs. However, we still ignore important factors that could not be included because of data limitations, such as costs associated with imbalances/empty legs or other route varying freight cost components, which lead to high freight costs in some regions (e.g. Pacific islands).

VC is taken from the output of the Modal Split model. The VOT metric is taken as a percentage of the value of the good to be transported in line with the findings of Hummels and Schaur (Hummels and Schaur, 2013). We set a VOT value per economic sector based on Hummels and Schaur (Hummels and Schaur, 2013) and De Jong *et al.* (de Jong *et al.*, 2010), which are summarised in Supplementary Table A2.8.

For the hinterland transport network, speed, time and distance costs are similar as used in Supplementary Note A2.1 and summarised in Supplementary Table A2.4-7. Dwell times and handling are used when transferring goods from one mode to the other, with values used summarised in Supplementary Table A2.4. Moreover, if ports in other countries are used, the border crossing times are added as additional dwell time (see Supplementary

Note A2.1). The time costs are found by dividing the distance with the mode-specific speed (Supplementary Table A2.3) and applying the time costs to this.

For the maritime transport network, we add speed, time and distance cost per vessel type, as shown in Supplementary Table A2.3-7. Port handling costs vary per good and across ports. We add vessel specific port handling costs to the individual port based on a database provided by the ITF-OECD (not publicly available), which is constructed as part of the ITF global freight model development (Martínez, Kauppila and Castaing, 2015). The total dwell time of goods at the port consist of the unloading/loading time and the dwell of cargo in the port (time between entering/leaving on the land-side and loading/unloading). The loading/unloading time is derived from AIS data, for which we take the median turnaround time of the different vessel types in a port. The dwell time for containers is set to 3 days for Group 1 countries and 6 days for Group 2 countries (Martínez, Kauppila and Castaing, 2015), but can be substantially higher for countries in Sub-Saharan Africa (up to 16 days). The dwell times of goods transported by other vessel types is more context-specific, but we use number as found in the literature. In general, we set dwell time in Group 2 countries as twice that of Group 1 countries. For transhipment, we assumes that the handling costs are 75% of the handling costs of importing/exporting. Transhipment dwell are commonly longer than importing/exporting (Ligteringen and Velsink, 2012; Raballand *et al.*, 2012), and we apply a factor 1.2 to the dwell times for importing/exporting.

Flow allocation procedure

The flow allocation is done by means of a capacity-constraint (all-or-nothing) shortest path routing approach using Dijkstra's shortest path algorithm (Dijkstra, 1959). We follow a step-wise approach too allocation flows per economic sector:

- Extract the sector-specific maritime trade flows between country pairs and disaggregate the flows to the centroids.
- Calculate the fraction of the five main vessel types for the economic sector and add the capacities at ports and maritime routes, the handling cost, dwell time, and time and distance costs to the maritime transport network. Moreover, select the VOT for the economic sector.
- Loop over the country pairs and allocate the trade flows between country centroids using the shortest path algorithm. If flows are allocated, reduce the capacity in the port nodes and on the maritime transport legs until capacity is reached.
- Repeat until all flows are allocated and store the all paths between O and D.
- In case certain ports are underutilised (allocation lower than port capacity) and others are overutilized (allocated more than port capacity), rebalance the allocation such that the error between the initial allocation and the port capacities is minimized.
- Repeat for the every economic sector, resulting in a flow allocation per economic sector.

Model validation

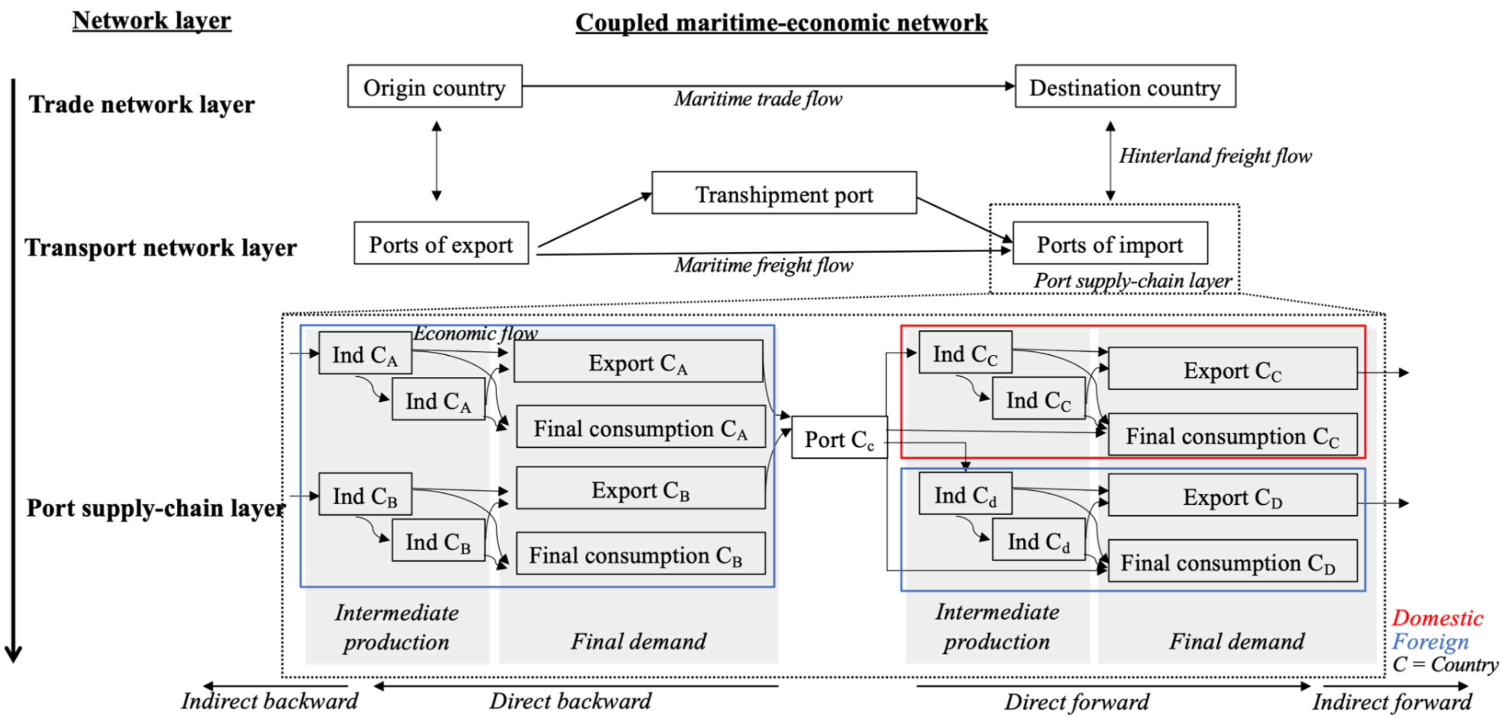
Validating the output of the transport model is complex, as there is no external dataset available to validate port-to-port trade flows. We therefore perform two types of external validation; (1) compare the distribution of trade across ports for four countries we have official data for (United States, United Kingdom, Japan, New Zealand), and (2) evaluate the flows through the Suez and Panama canal.

The aim of the model is to evaluate the share of maritime that is going in and out the ports to meet a countries import and export. We collected data for four countries (United States, United Kingdom, Japan, New Zealand), and derive, per sector, the cumulative distribution of maritime trade across the country's ports and compared this to the model output. Results are shown in Supplementary Figure A2.11, showing an excellent fit for the United Kingdom and the United States. For New Zealand, all sectors show a good agreement, except the export of 'Other Manufacturing' products. For Japan, the all sectors show a good agreement, except the imports of 'Textiles and wearing apparel' and the exports of 'Food and Beverages'. However, given all model uncertainties, the comparison shows that the model is able to distribute sector-specific imports and exports to the correct ports.

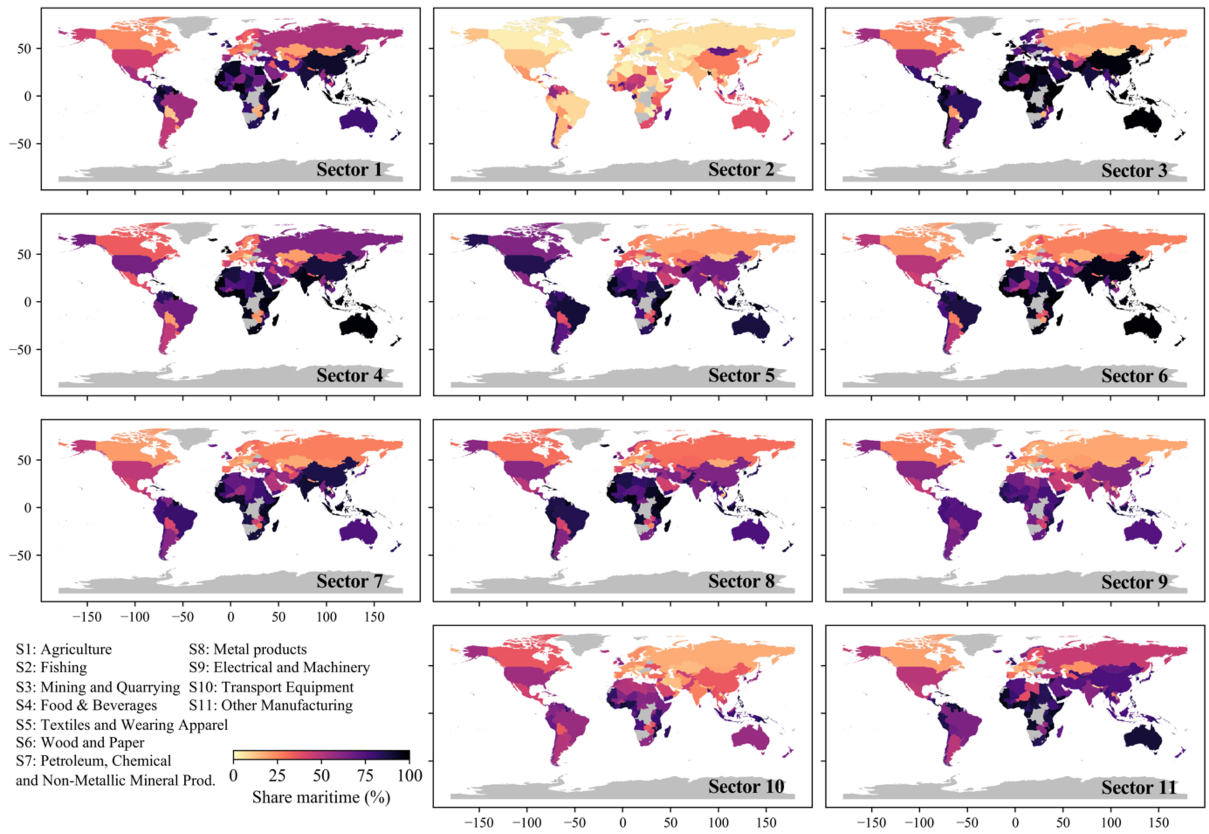
In addition, we evaluate whether the flows through the Panama and Suez canal are in line with reality, which gives us an indication whether the flow distribution between ports globally is realistic. Our model estimates that around 1.1 trillion USD (13.8% of maritime trade in value terms) and 1.04 billion tonnes (10.8% of maritime trade in quantity terms) flows through the Suez canal. According to official records, more than 1 trillion USD goes through the Suez canal every year, which equalled 998 million tonnes in 2015[11]. Moreover, we predict that around 490 million USD (6.2% of maritime trade in value terms) and 461 million tonnes (4.8% of maritime trade in quantity terms) flows through the Panama canal every year. According to the Panama Canal Authority, in 2015 reported a flow of 340 million tonnes through the canal and 470 million tonnes in 2019[12]. The top 10 countries using the Panama canal in 2021 are reported to be the United States, China, Japan, South-Korea, Chile, Mexico, Peru, Colombia, Canada and Ecuador[13]. These 10 countries are also the top 10 countries our model simulation predicts in terms of quantity (through slightly different order).

[11] https://www.suezcanal.gov.eg/English/Navigation/Pages/NavigationStatistics.aspx
[12] https://www.pancanal.com/eng/general/reporte-anual/index.html
[13] https://www.pancanal.com/eng/op/transit-stats/2021/Table-10.pdf

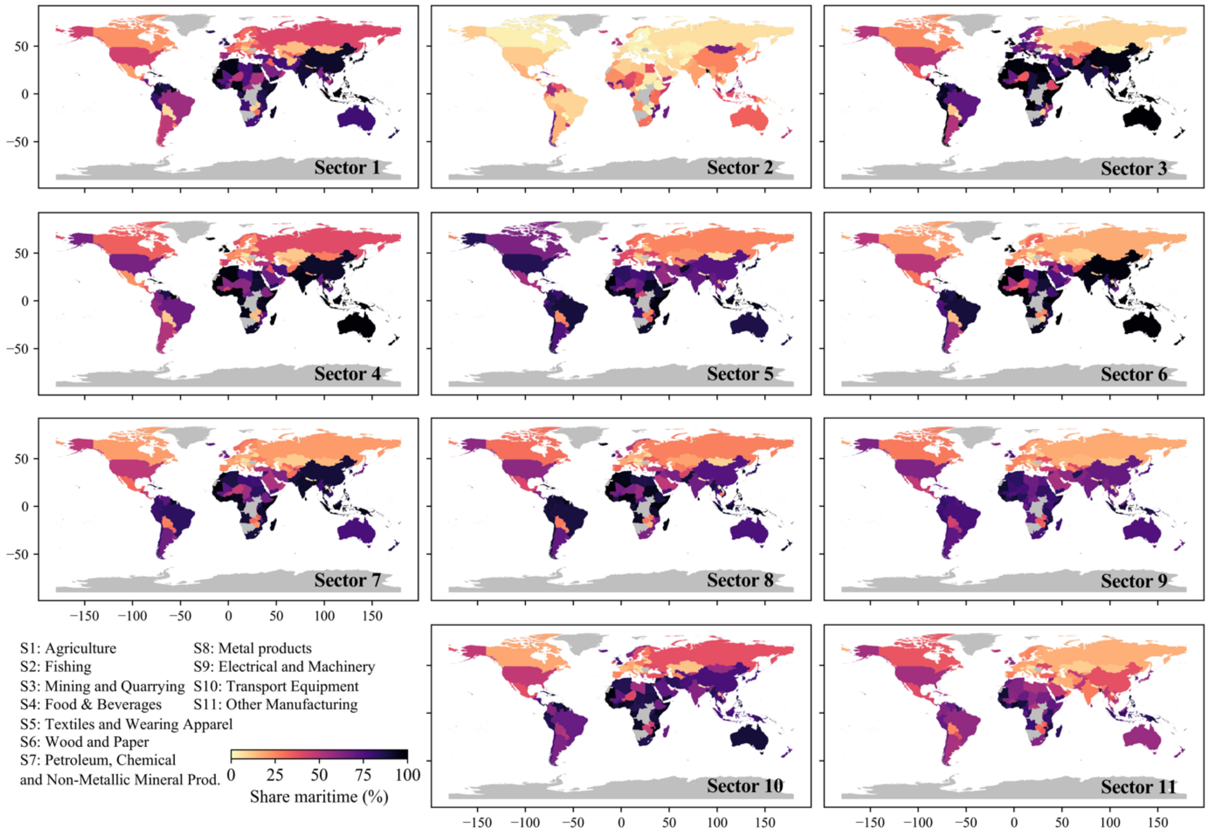
Supplementary Figures



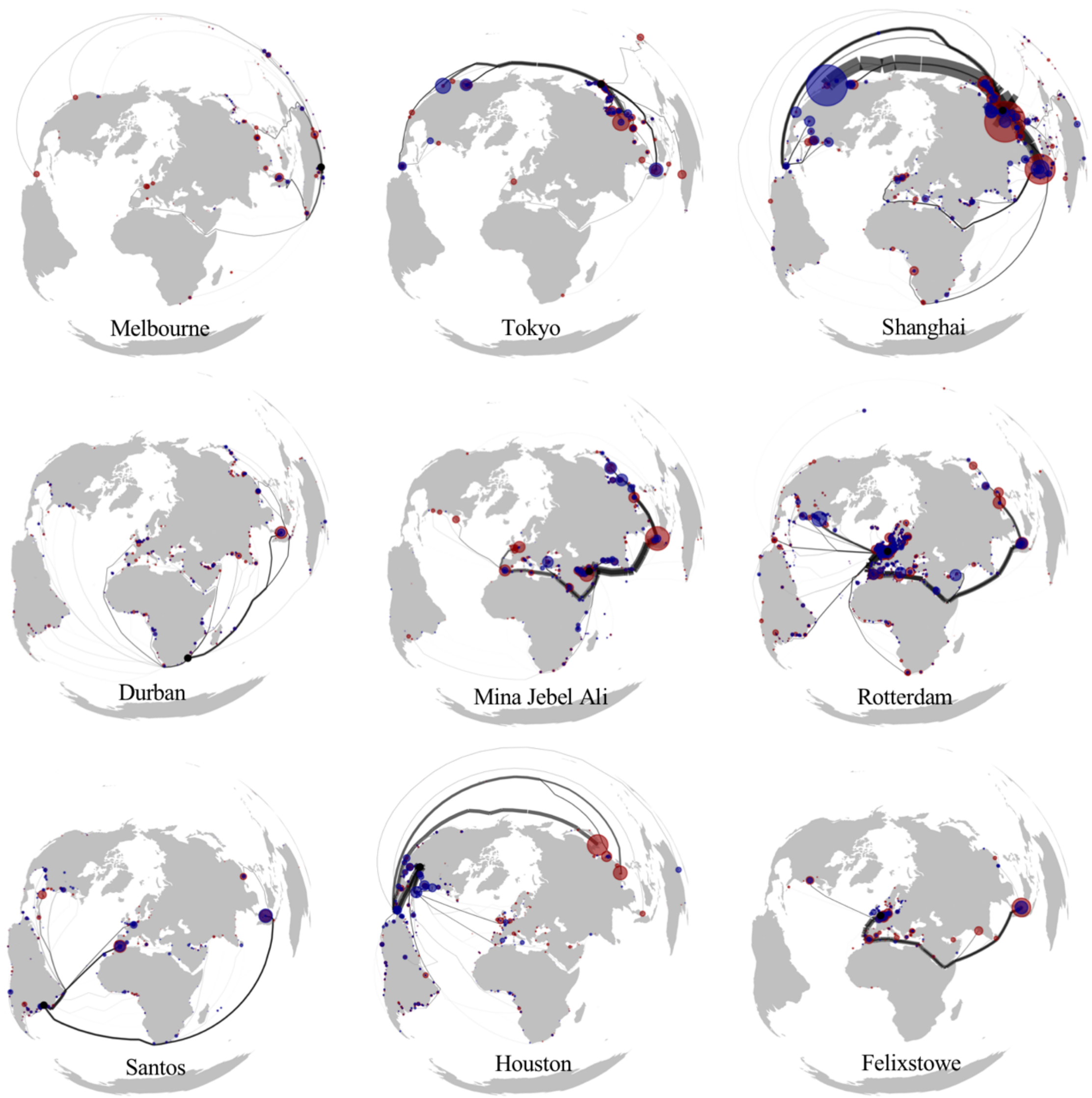
Supplementary Figure A2.1: Conceptual framework multi-layered maritime-economic network. The top layer shows the 'Trade network layer', which is constructed using the modal split model. The layer describes the size of the maritime trade flow between two countries. The middle layer shows the 'Transport network layer', which describes the freight flow allocation on the maritime and hinterland transport network. The bottom layer is the 'Port supply-chain layer' which describes how economic flows going in and out ports are used in the economy, which is done on a port by port basis. This layer shows an example port in country C (Port Cc) that receives goods from country A and B, which were produced using intermediate production (Ind) in these countries. The flows going through port Cc are then being used as intermediate products in country C (which are then further exported or consumed) or go directly into final consumption in country C. Alternatively, it could be that the flows are going to another country, country D, which is dependent on port C via an hinterland transport network. We further distinguish between domestic economic flows (e.g. flows between the port and the country it is located it) or foreign economic flows (flows coming from or going to foreign economies). Similarly, we can distinguish between direct and indirect backward/forward flows. Direct flows feed/come out of the port directly, while economic flows further downstream/upstream in the supply chain are considered indirect flows



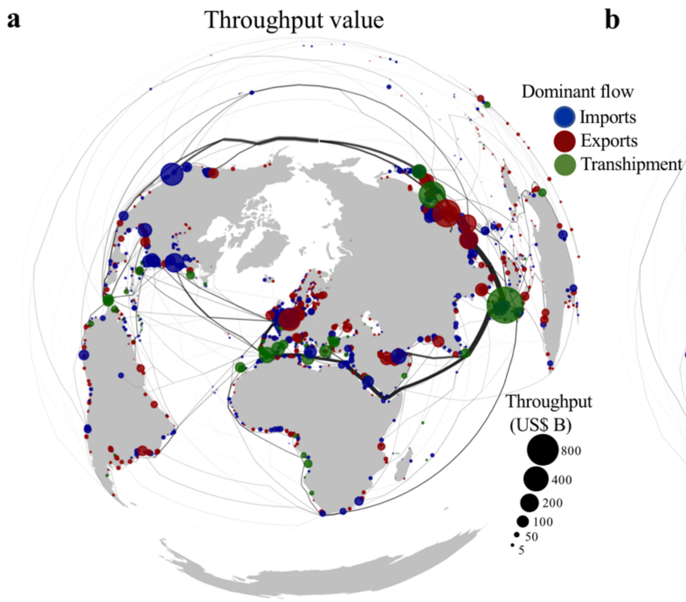
Supplementary Figure A2.2: Share of maritime trade in country imports. The share of maritime transport in total imports for the 2015 trade network. Each panel shows the percentages for a particular economic sector. Grey indicates no data.



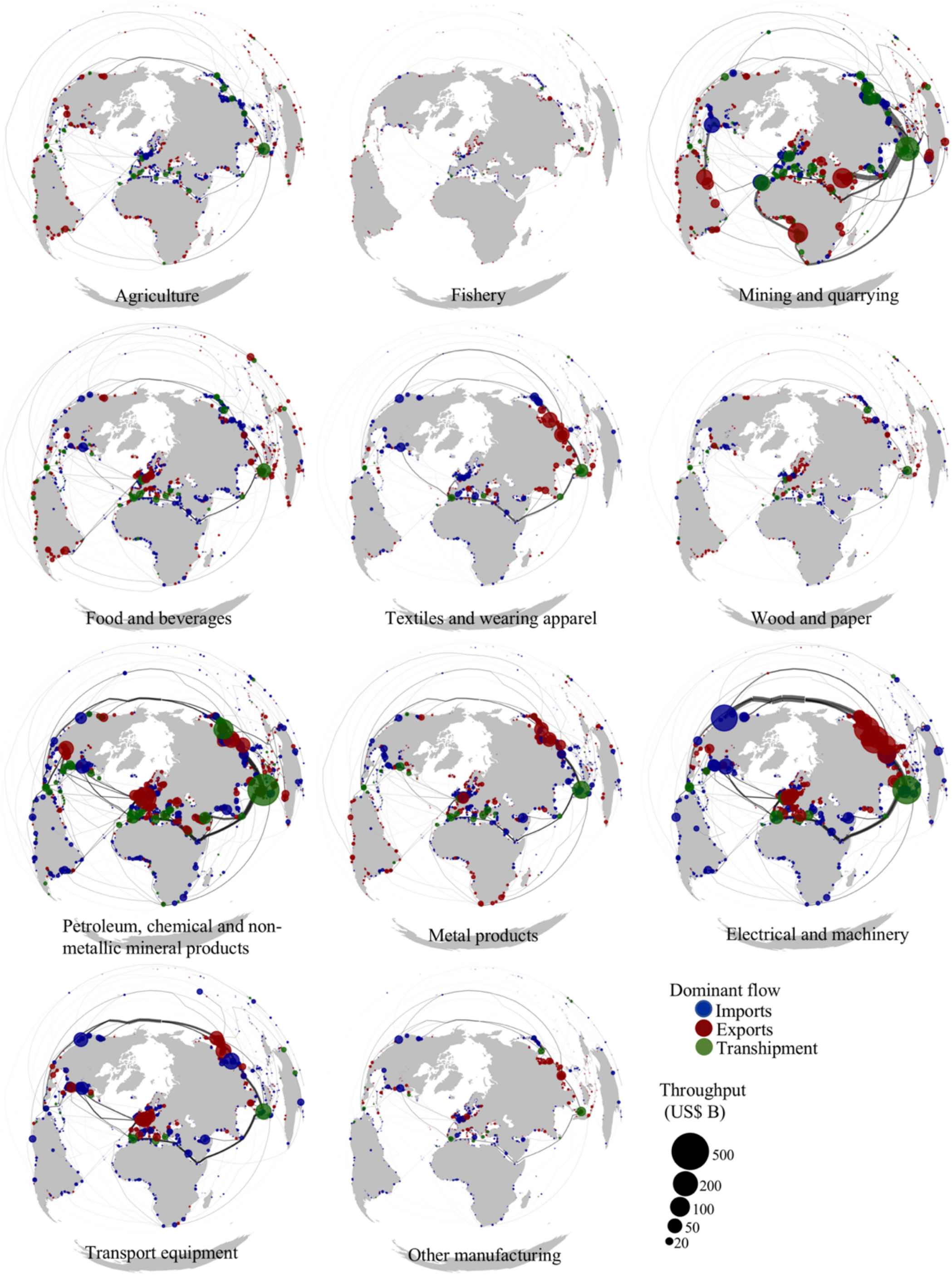
Supplementary Figure A2.3: Share of maritime trade in country exports. The share of maritime transport in total exports for the 2015 trade network. Each panel shows the percentages for a particular economic sector. Grey indicates no data.



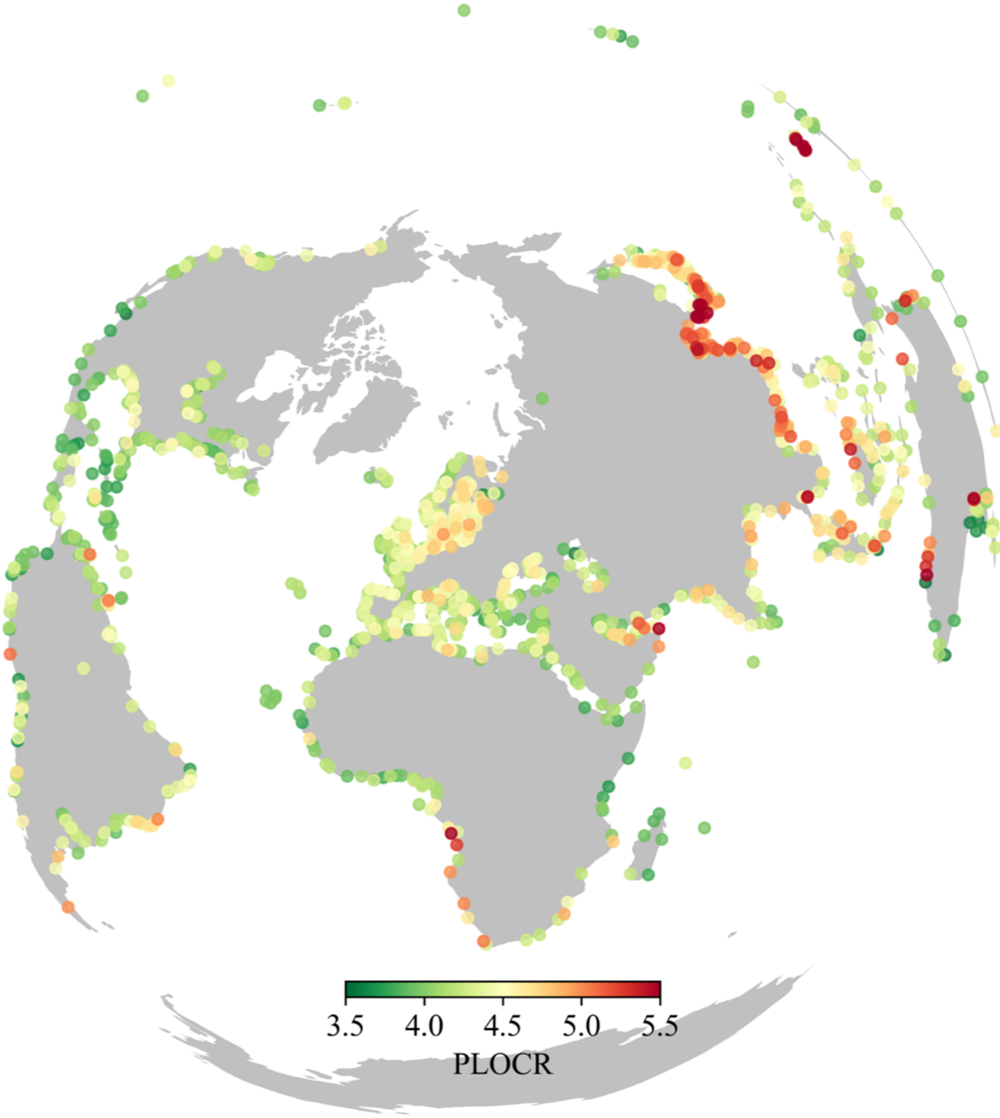
Supplementary Figure A2.4: Examples of port's spatial connectivity. The top 200 largest importing (blue, left) and exporting (red, right) trade flows to and from a port, including the location of the origin/destination port. Examples are shown for 9 ports globally.



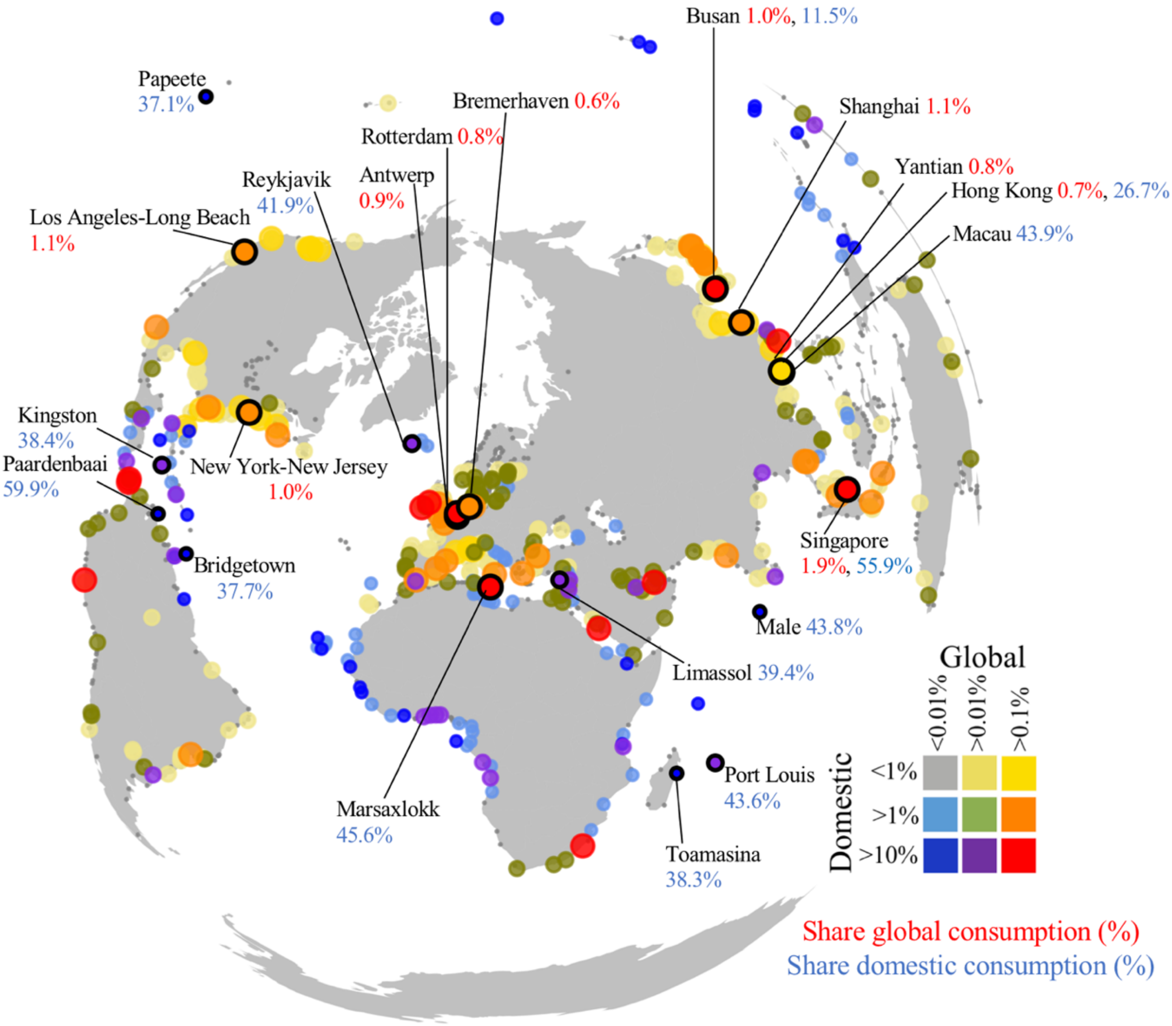
Supplementary Figure A2.5: Global maritime transport network. (a) The global maritime transport network, consisting of the port-level throughput and dominant flow direction, and the maritime transport routes used. Size of dots and line thickness related to value flows through a port or on a route. (b) Same as (a) but expressed in quantity terms.



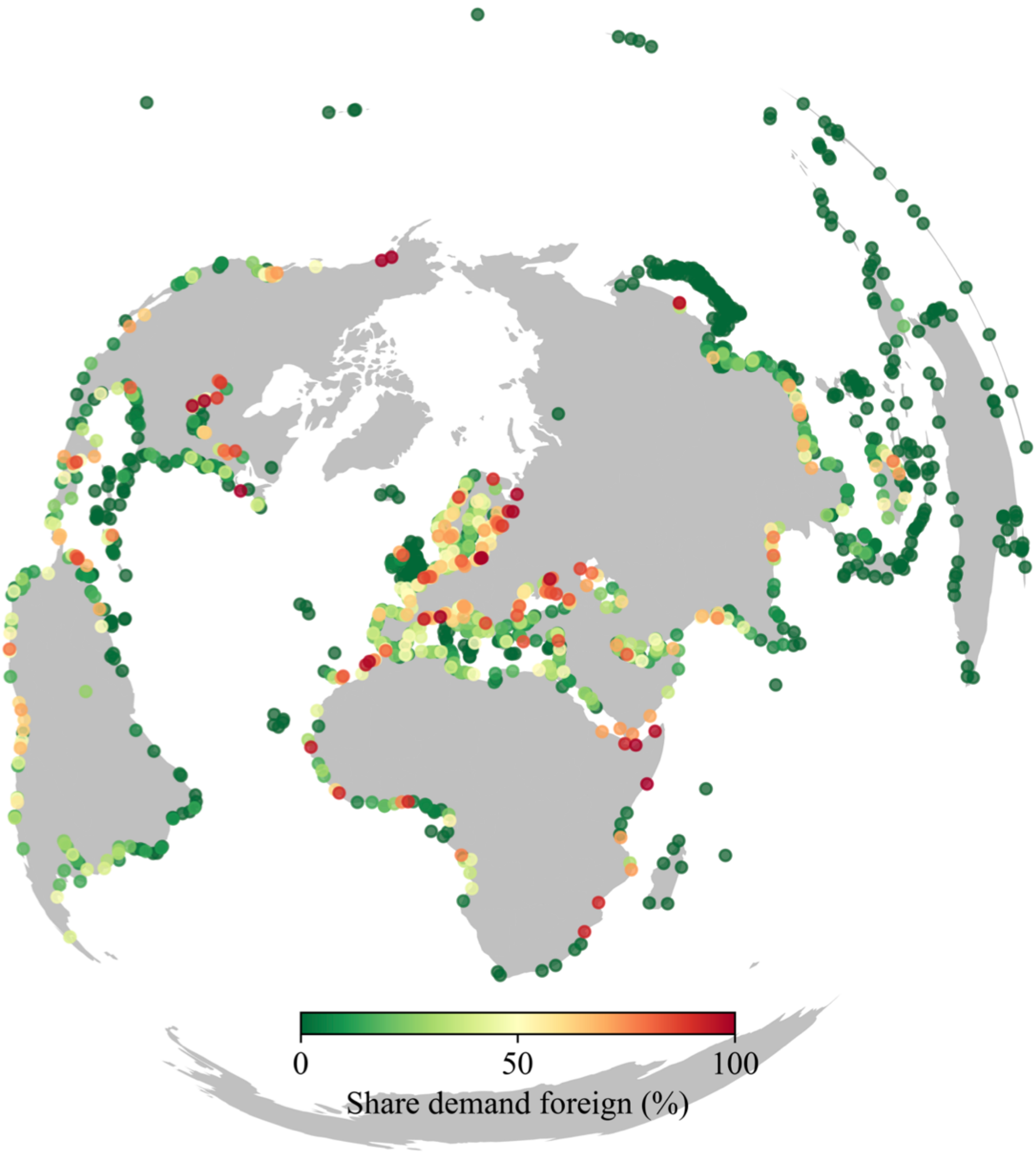
Supplementary Figure A2.6: Global maritime transport network per industry sector**.** The global maritime transport network, consisting of the port-level throughput and dominant flow direction, and the maritime transport routes used per economic sector. Size of dots and line thickness related to value flows through a port or on a route.



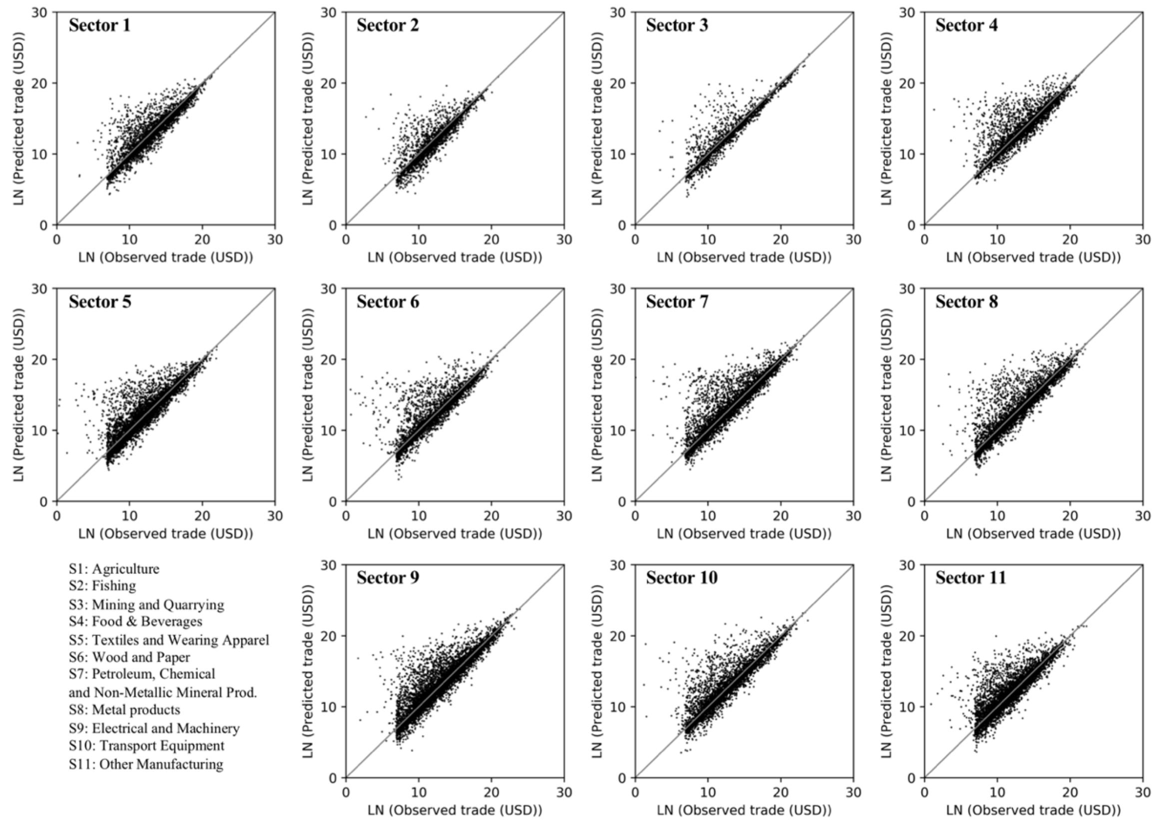
Supplementary Figure A2.7: Geographical distribution of PLOCR values. The geographical location of ports with their associated relative port-level output coefficient (PLOCR), indicating the amount of industry output embedded in every dollar trade flow going through a port.



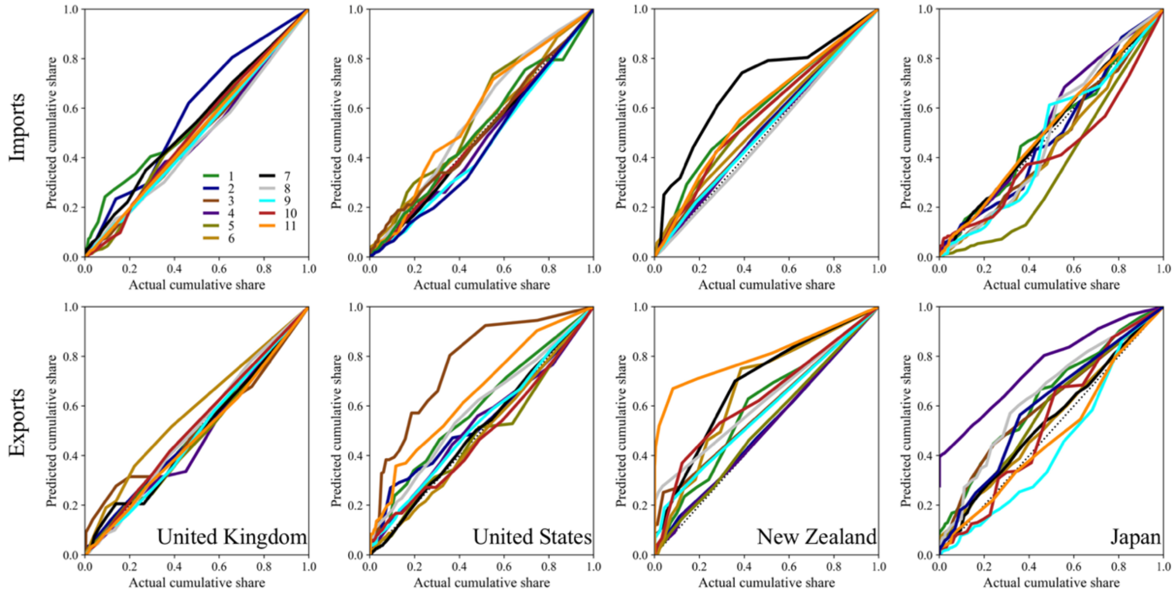
Supplementary Figure A2.8: Distribution of the domestically and globally critical ports in terms of final consumption. The importance of trade flows going through ports in terms of its contribution to the domestic consumption as a percentage of total domestic consumption and global consumption as a percentage of total global consumption. The ten ports most critical ports in terms of domestic and global consumption are highlighted together with the associated percentage value (domestic in blue, global in red).



Supplementary Figure A2.9: Share of foreign demand in port-level import coefficient. The share of port-level import coefficient that is linked to a foreign economy because of land-based connections.



Supplementary Figure A2.10: Validation modal split model. Validation plots showing the actual maritime trade flows based on UN Comtrade data(United Nations Statistical Division, 2020) and predicted maritime trade flows using the mode prediction model.



Supplementary Figure A2.11: Validation trade distribution. Validation plots showing the actual distribution of trade over the ports in a country and the predicted distribution based on the maritime transport model. This is based on detailed port-level, sector-specific, trade flows which are available for four countries; United Kingdom, United States, New Zealand and Japan, United States. The top panel represent imports, whereas the bottom panel represent exports.

Supplementary Tables

Supplementary Table A2.1: Overview of economic sectors used in this study.

Sector	Description
1	Agriculture
2	Fishing
3	Mining and Quarrying
4	Food & Beverages
5	Textiles and Wearing Apparel
6	Wood and Paper
7	Petroleum, Chemical and Non-Metallic Mineral Products
8	Metal Products
9	Electrical and Machinery
10	Transport Equipment
11	Other Manufacturing

Supplementary Table A2.2: Overview of the concentration of port-level trade per sector. The number represent the number of ports (out of the 1380 ports) that contribute to 10%, 50% and 90% of trade (imports and exports).

	Import			**Export**		
Sector	10%	50%	90%	10%	50%	90%
1	5	60	344	3	42	267
2	2	24	168	2	33	217
3	2	33	199	1	19	188
4	5	74	392	5	50	309
5	2	19	128	1	7	92
6	4	39	221	3	29	187
7	4	72	371	3	46	294
8	4	41	272	3	38	236
9	1	22	177	2	17	124
10	3	27	181	2	15	124
11	2	19	142	1	13	99
All	4	56	378	3	48	366

Supplementary Table A2.3: Speed per transport mode used in modal split model and transport model.

Mode	Group	Parameter	Group 1 countries	Group 2 countries	Source
Air		Speed (km/h)	750	750	(Martínez, Kauppila and Castaing, 2015)
Road	Primary road	Speed (km/h)	80	70	(Martínez, Kauppila and Castaing, 2015)
	Secondary road	Speed (km/h)	65	55	(Martínez, Kauppila and Castaing, 2015)
	Beltway/national road	Speed (km/h)	40	30	(Martínez, Kauppila and Castaing, 2015)
	Tracks/unpaved roads	Speed (km/h)	10	5	(Martínez, Kauppila and Castaing, 2015)
Maritime	Container	Speed (km/h)	30	30	(Ligteringen and Velsink, 2012)
	Dry Bulk	Speed (km/h)	20	20	(Ligteringen and Velsink, 2012)
	General Cargo	Speed (km/h)	22	22	(Ligteringen and Velsink, 2012)
	RoRo	Speed (km/h)	28	28	(Ligteringen and Velsink, 2012)
	Liquid bulk	Speed (km/h)	20	20	(Ligteringen and Velsink, 2012)
IWW		Speed (km/h)	8	8	(Martínez, Kauppila and Castaing, 2015)

Note: Group 1 countries include European countries, Japan, Australia, Canada and United States. Group 2 countries include the rest of the world.

Supplementary Table A2.4: Dwell time and handling costs hinterland network.

From	To	Dwell time (h)	Handling cost (USD per tonnes)	Source
Centroid	Road	10	4	(de Jong *et al.*, 2010), (Martínez, Kauppila and Castaing, 2015)
Road	Rail	32	5	(de Jong *et al.*, 2010), (Martínez, Kauppila and Castaing, 2015)
River port	IWW	120	1	(de Jong *et al.*, 2010), (Blauwens and Van de Voorde, 1988)
Road	Port	50	4	(de Jong *et al.*, 2010), (Martínez, Kauppila and Castaing, 2015)
Rail	Port	50	5	(de Jong *et al.*, 2010), (Martínez, Kauppila and Castaing, 2015)
Port	IWW	120	1	(de Jong *et al.*, 2010), (Blauwens and Van de Voorde, 1988)
Road	Air	40	4	(de Jong *et al.*, 2010), (Martínez, Kauppila and Castaing, 2015)
Border	Border	Country-specific	0	(World Bank, 2020a)

Supplementary Table A2.5: Dwell times and handling costs at ports and airports. Note: Group 1 countries include European countries, Japan, Australia, Canada and United States. Group 2 countries include the rest of the world.

Mode	Group	Parameter	Group 1 countries	Group 2 countries	Source
Air		Handling cost (USD per tonnes)	450	450	(de Jong *et al.*, 2010)
		Dwell time (h)	4	48	(Martínez, Kauppila and Castaing, 2015)
		Transhipment dwell time (h)	18	18	(Meijs, 2017)
Maritime	Container	Handling cost (USD per tonnes)	Port-specific	Port-specific	ITF-OECD
		Cargo dwell time (h)	3	6	(Ligteringen and Velsink, 2012)
		Vessel turnaround time (h)	Port-specific	Port-specific	AIS data
	Dry Bulk	Handling cost (USD per tonnes)	Port-specific	Port-specific	ITF-OECD
		Cargo dwell time (h)	15	30	(Ligteringen and Velsink, 2012)
		Vessel turnaround time (h)	Port-specific	Port-specific	AIS data
	General Cargo	Handling cost (USD per tonnes)	Port-specific	Port-specific	ITF-OECD
		Cargo dwell time (h)	8	16	(Ligteringen and Velsink, 2012)
		Vessel turnaround time (h)	Port-specific	Port-specific	AIS data
	RoRo	Handling cost (USD per tonnes)	Port-specific	Port-specific	ITF-OECD
		Cargo dwell time (h)	5	10	(Ligteringen and Velsink, 2012)
		Vessel turnaround time (h)	Port-specific	Port-specific	AIS data
	Liquid bulk	Handling cost (USD per tonnes)	Port-specific	Port-specific	ITF-OECD
		Cargo dwell time (h)	2	4	(Ligteringen and Velsink, 2012)
		Vessel turnaround time (h)	Port-specific	Port-specific	AIS data

Supplementary Table A2.6: Distance and time costs per transport mode

Mode	Group	Parameter	Value	Source
Air		Distance costs (USD per t-km)	0.2	(van der Meulen *et al.*, 2020)
		Time costs (USD per t-h)	135	(van der Meulen *et al.*, 2020)
Maritime	Container	Distance costs (USD per t-km)	0.002	(van der Meulen *et al.*, 2020)
		Time costs (USD per t-h)	0.03	(van der Meulen *et al.*, 2020)
	Dry Bulk	Distance costs (USD per t-km)	0.004	(van der Meulen *et al.*, 2020)
		Time costs (USD per t-h)	0.06	(van der Meulen *et al.*, 2020)
	General Cargo	Distance costs (USD per t-km)	0.002	(van der Meulen *et al.*, 2020)
		Time costs (USD per t-h)	0.03	(van der Meulen *et al.*, 2020)
	RoRo	Distance costs (USD per t-km)	0.002	(van der Meulen *et al.*, 2020)
		Time costs (USD per t-h)	0.03	(van der Meulen *et al.*, 2020)
	Liquid bulk	Distance costs (USD per t-km)	0.006	(van der Meulen *et al.*, 2020)
		Time costs (USD per t-h)	0.11	(van der Meulen *et al.*, 2020)
Road		Distance costs (USD per t-km)	Country-specific	ITF-OECD
		Time costs (USD per t-h)	4	(van der Meulen *et al.*, 2020)
Rail		Distance costs (USD per t-km)	Country-specific	ITF-OECD
		Time costs (USD per t-h)	1	(van der Meulen *et al.*, 2020)
IWW		Distance costs (USD per t-km)	Country-specific	ITF-OECD
		Time costs (USD per t-h)	0.2	(van der Meulen *et al.*, 2020)

Supplementary Table A2.7: Value of time (VOT) expressed as the percentage of product value per day

Sector number	Description	VOT (%)
1	Agriculture	1.0
2	Fishing	3.1
3	Mining and Quarrying	0.5
4	Food & Beverages	3.1
5	Textiles and Wearing Apparel	1.0
6	Wood and Paper	1.0
7	Petroleum, Chemical and Non-Metallic Mineral Products	1.0
8	Metal Products	1.0
9	Electrical and Machinery	2.0
10	Transport Equipment	4.3
11	Other Manufacturing	2.0

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APPENDIX 3: SUPPLEMENTARY INFORMATION 'MULTI-HAZARD RISK TO GLOBAL PORT INFRASTRUCTURE AND RESULTING TRADE AND LOGISTICS LOSSES'

Contains:

Supplementary Note A3.1

Supplementary Figure A3.1-9

Supplementary Table A3.1-4

Supplementary Note A3.1

Port areas

The total port area mapped globally equals 4521 km^2. In Supplementary Figure A3.9, we have regrouped the 16 land-use classes into seven land-use classes and plotted the total area per continent. The Liquid (23.7%), Raw (15.4%) and Container (13.6%) land-use classes contribute most to the size of global port areas. The industry areas add an additional 4345 km^2 of port areas to the database. In Supplementary Figure A3.8, the Industry area per continent is shown. Most industry is concentrated in Europe, North-America and Asia, while the Middle-East also has a large number of industrial facilities in port areas (mainly oil facilities).

The mapped port area is considerably larger than previous estimates of global port areas that used a simple scaling relationship between throughput and port area (Hanson and Nicholls, 2020). For instance, Hanson and Nicholls (Hanson and Nicholls, 2020) predicted the global port area to be 1364 km^2. In their comparison of country-level port areas (Table 3 in Hanson and Nicholls, 2020), they concluded that their estimates were overall lower than other studies. For comparison, we replicate this table and add the results of our mapping exercise to the table (see Supplementary Table A3.3). We compare the total port areas for 16 countries that includes (1) all land-use types, (2) all land-use types except 'Industry', (3) all land-use types except 'Industry', 'Storage', and 'Other' land-use areas . As can be seen from Supplementary Table A3.3, our estimates are considerably higher than all other studies, although it does depend on what land-use types are considered. Hence, comparison across studies is difficult and depends on the definition of port land-use included. Still, for the 16 countries considered, our estimates are 4.8, 2.5 and 2.1 times higher, respectively, compared to (1) for the three groups of land-use types. In particular, the discrepancies are larger for countries like China, the United States and Japan, underlining that simple scaling relationships across countries should be adopted with care.

Coastal structures database

We include three different types of coastal structures: (1) coastal breakwaters that function as an inlet (referred to as 'inlet'), (2) coastal breakwaters that protect against waves (referred to as 'breakwater'), and (3) coastal seawalls alongside port terminals that protect against waves and overtopping (referred to as 'seawall'). To construct a geospatial database of coastal structures within port areas, we first extract data from OpenStreetMap under the tag 'breakwater'. However, a lot of breakwaters are wrongly tagged (e.g. coastal groynes, revetment, etc.). Therefore, we manually checked all tagged breakwaters and remove wrongly tagged ones, while supplementing missing coastal structures (adding 'inlet' and 'seawall' structures). This new geospatial dataset consists of 1410 coastal structures, represented as either lines or polygons.

Wave height operational threshold

We derive wave parameters (significant wave height, wave period and wave direction) from ERA5 global reanalysis wave data at 6h interval from 1979-2018 (Hersbach *et al.*, 2020). For every port, we extract data at the closest grid cell and create a daily time series by selecting the wave parameters concurrent with the daily maximum wave height.

To estimate the wave height at the entrance channel and in front of the coastal protection works, we propagate the wave parameters at the grid cell to the entrance of the channel and the coastal protection works. The wave height and direction change as they propagate from the deep sea towards the coast (wave period is assumed to be constant) owing to the influence of shoaling and refraction (Dean and Dalrymple, 2001). Under the assumption of a straight and parallel offshore bathymetry, we can use the Snell's law to propagate wave height and wave direction from the deep sea depth towards any other depth and orientation (Dean and Dalrymple, 2001). A similar assumption was adopted in previous work (Izaguirre *et al.*, 2021), as it was recognized that it is the only approach feasible given available global input.

The depth at the grid cell and at the coastal protection works are taken from the GEBCO 2020 global bathymetry data (Weatherall *et al.*, 2015). For the coastal protection works, we assume the design depth to be the deepest point along a 15m buffer around the coastal structure. To check whether the estimated design depths approximate the design depths of existing breakwaters, we match our breakwater database with breakwaters included in the 'International Breakwater Directory' (Allsop, Cork and Verhagen, 2010). We find 42 overlapping breakwaters with a design depth input in the database. We find that the estimated and observed design depths correspond well (Pearson correlation coefficient of 0.54), keeping in mind that the GEBCO dataset has a 450m resolution. For the navigation channel we assume the depth to be equal to 1.2 times the draft of the largest vessel entering the port (dredged channel), except if the natural bathymetry is deeper than the design depth of the navigation channel. In that case we adopt the natural bathymetry depth. To obtain the orientation of the coastal protection work/navigation channel, we find the orthogonal angle of the orientation of the coastline, which is taken from the global, self-consistent, hierarchical, high-resolution shoreline database (GSHHG) (Wessel and Smith, 1996) (which in some cases includes the breakwaters as part of the coastline). We use this data in combination with Snell's law (see (Dean and Dalrymple, 2001) for formulation) to find the wave height and wave angle in the navigation channel and at the toe of the coastal protection works. Wave propagation is constrained by wave breaking (when waves reach shallow water) using a wave breaking criteria ($H_b = d_b/1.28$) with H_b the wave breaking height and d_b the depth at breaking.

Based on the critical wave threshold adopted per port, we find the number of days the wave height exceeds this threshold over the historical time period. We use this to estimate the annual frequency of exceedance per port.

Overtopping operational threshold

Overtopping is a complex phenomenon driven by the interaction of waves and surges on a coastal structure (van der Meer, 1992, 2011). Most ports have breakwaters that protect the port basin from unwanted wave transmission into the harbour. Ports without a breakwater often have seawalls alongside the port terminals to minimize the probability of wave overtopping and resulting impacts on goods and operations. The design of breakwaters and other coastal protection works vary considerably globally and are dependent, among others, on the local hydrodynamic conditions, the type of structure (e.g. caisson, rubble mound), type of armour layer (e.g. rock, Tetrapods, Xbloc), inclusion of a berm, and the lifetime and importance of the coastal protection work (van der Meer, 2011). Given that this type of data is not readily available globally, we propose an alternative way to evaluate the risk of overtopping for coastal protection works. For every coastal structure exposed to overtopping in our database, we first create a standard design (in particular the design freeboard) based on engineering design principles given the wave and surge inputs. We then re-evaluate the risk of overtopping to the design structure for the combined wave and surge time series.

The wave data, propagated to the coastal structures, are taken similar as described in the derivation of the wave height operational thresholds. We add surge and tide data to the wave time series, obtained from latest Global Tide and Surge Reanalysis (GTSR) model data (Muis *et al.*, 2020), which is a global reanalysis product of extreme water levels (EWL, tide+surge) for 1979-2018. Wave set-up/run-up is not added to the EWL data, as this is implicitly included in wave overtopping formulas (EurOtop, 2018).

As described above, instead of obtaining information on the dimensions of all coastal protection works, we construct a hypothetical design based on engineering principles and the local hydrodynamic input. This also prevents introducing errors due to bias in the input parameters (wave and surge data). We distinguish between two types of structures: an armoured breakwater ('breakwater' type) and an armoured seawall ('seawall' type), which have similar design principles except that in the case of a breakwater an additional correction factor is added for the presence of a permeable crest berm.

Wave height is the major design parameter for overtopping of coastal structures. A number of assumptions are made. First, all coastal structures are assumed to have a 50 year lifetime with a 10% probability of failure over this lifetime, which is a common value for breakwaters protecting commercial ports (Falk and Dalsgaard, 2005). This implies a design wave height with a 475 year return period (following a standard Poisson distribution). To find the design wave height, we fit an extreme value distribution to the annual maxima of wave height at the toe of the coastal structure. We decided to use a Gumbel distribution, after also testing a Weibull distribution, and both distributions with a Peak over Threshold (PoT) method (with the threshold at the 99^{th} percentile). The annual maxima method in combination with the Gumbel distribution results in design wave heights that are closest to design wave height of 37 georeferenced breakwaters included in the 'International Breakwater Directory' (Allsop, Cork and Verhagen, 2010). To find the corresponding wave period, we fit a regression model between wave period and the square root of the wave height ($Tm \sim H^{0.5}$) and use this to extrapolate the wave period. The design wave direction is set to the median wave direction associated with the annual maximum wave events. The design storm surge is set to be the maximum storm surge observed during any of the annual maximum wave events.

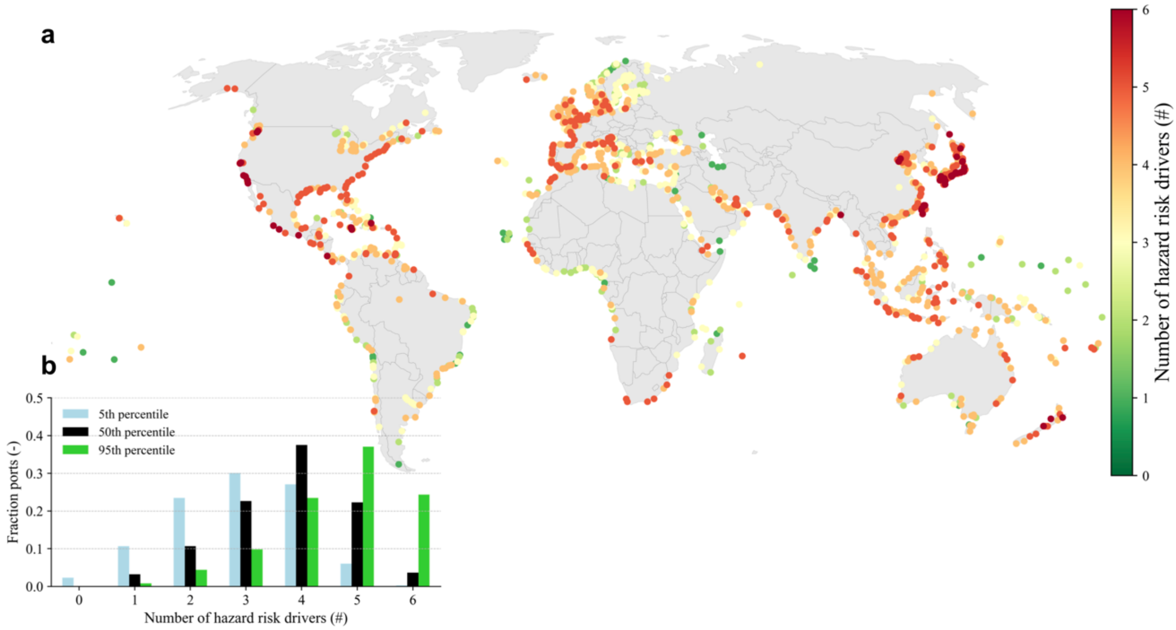
To estimate the freeboard height of the structure (main design parameter), we use the overtopping formulas used in the HR Wallingford design manual of wave overtopping (Wallingford, 1999). These formulas are similar as the more recent formulas adopted in the Eurotop manual (EurOtop, 2018), except that the Eurotop formulas use spectral wave height as design parameter (instead of significant wave height), which is not available in the wave model output. All structures are assumed to have a 1:2 slope and breakwater have a crest width/design wave height ratio of 1.7. These design criteria are obtained after inspecting known breakwater designs that are included in the 'International Breakwater Directory' (Allsop, Cork and Verhagen, 2010). We include a surface roughness of 0.5 to the design, which corresponds to having an armour layer composed of rock (with permeable core), cubes, Cubipods or HARO's (EurOtop, 2018). Moreover, the correction factor due to oblique waves is based on the EurOtop manual, given that this formula is considered to be superior (the formula in Wallingford 1999 was based on limited research).

Based on the design wave conditions and design parameters, we find the design freeboard for wave overtopping, after which we add the design surge to this freeboard. We use this design freeboard to estimate daily overtopping volumes using the combined wave and surge time series and estimate the exceedance of the tolerable overtopping threshold. The frequency of yearly exceedance is adopted to assess the number of downtime days.

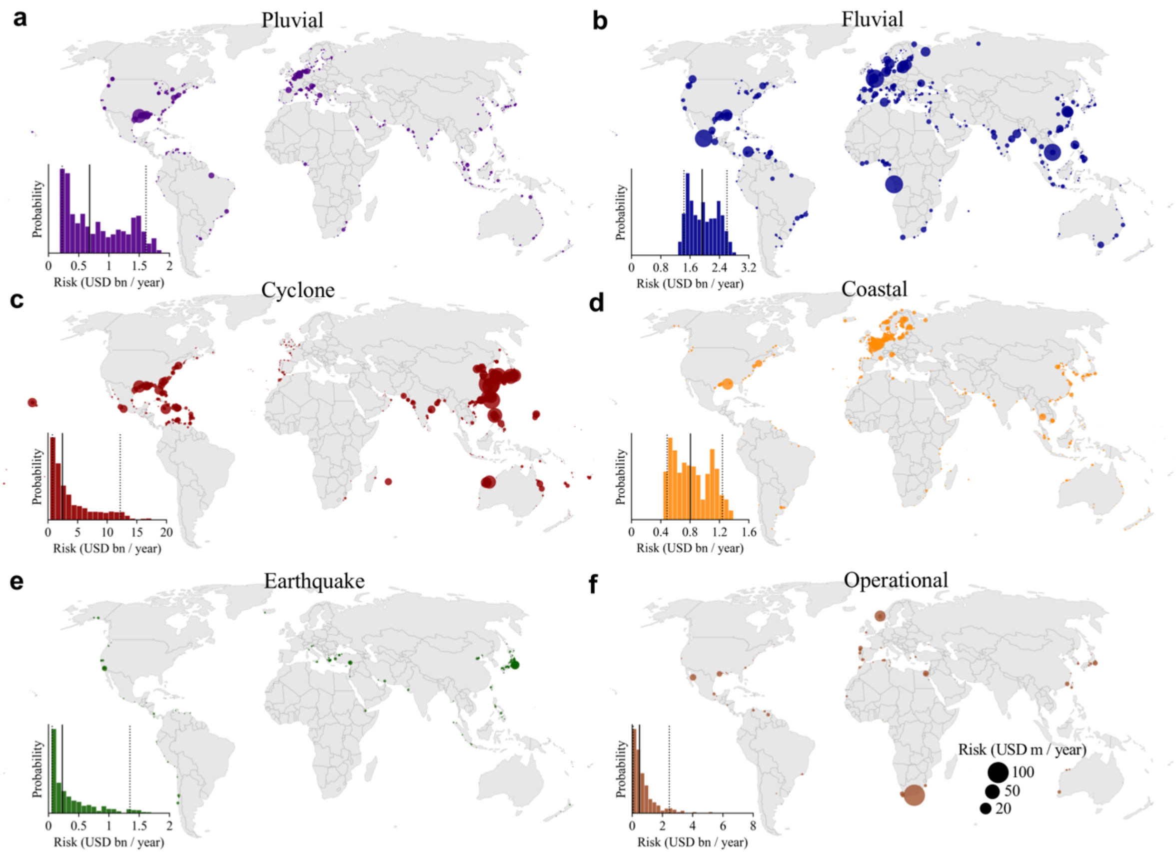
Sensitivity analysis global estimates

Supplementary Table A3.4 summarizes the results of the variance-based sensitivity analysis for the global port-specific and trade risk estimates. The top10 most sensitive model parameters are highlighted in bold. As can be seen, the uncertainty in the cyclone fragility curve is by far the leading uncertainty parameter for both metrics, although less important for trade risk compared to port-specific. As expected, the recovery duration curves and maximum recovery values contribute more to the variance of trade risk, as they directly influence downtime, compared to port-specific, for which they indirectly contribute to logistics losses. The maximum damage values are negligible for trade risk, as it does not affect downtime, but it is important for the variance in port-specific, in particular General Cargo and Industry maximum damage values.

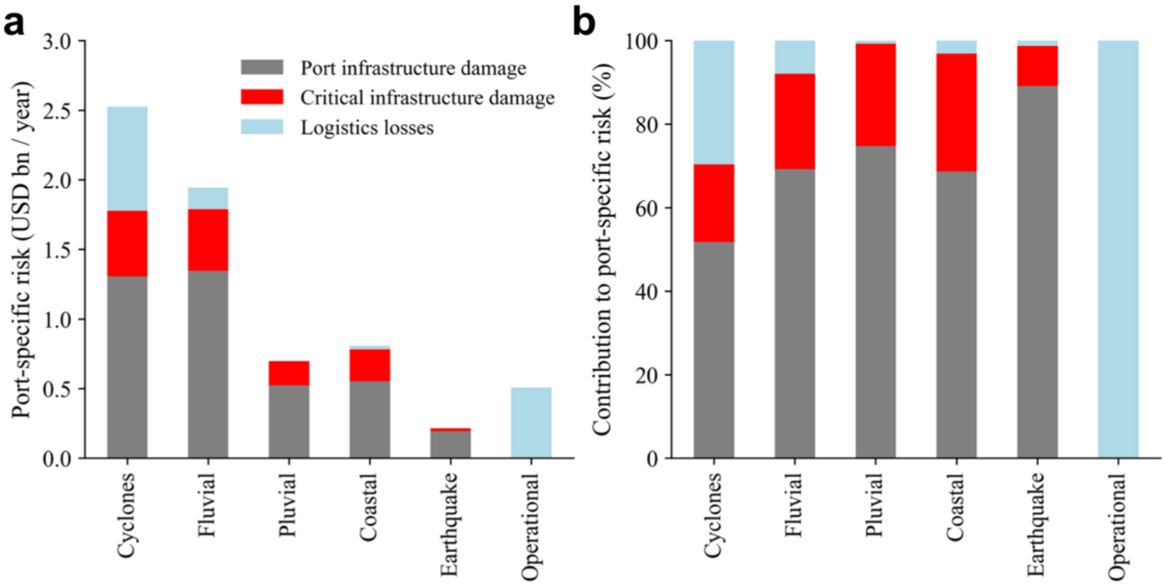
Supplementary Figures



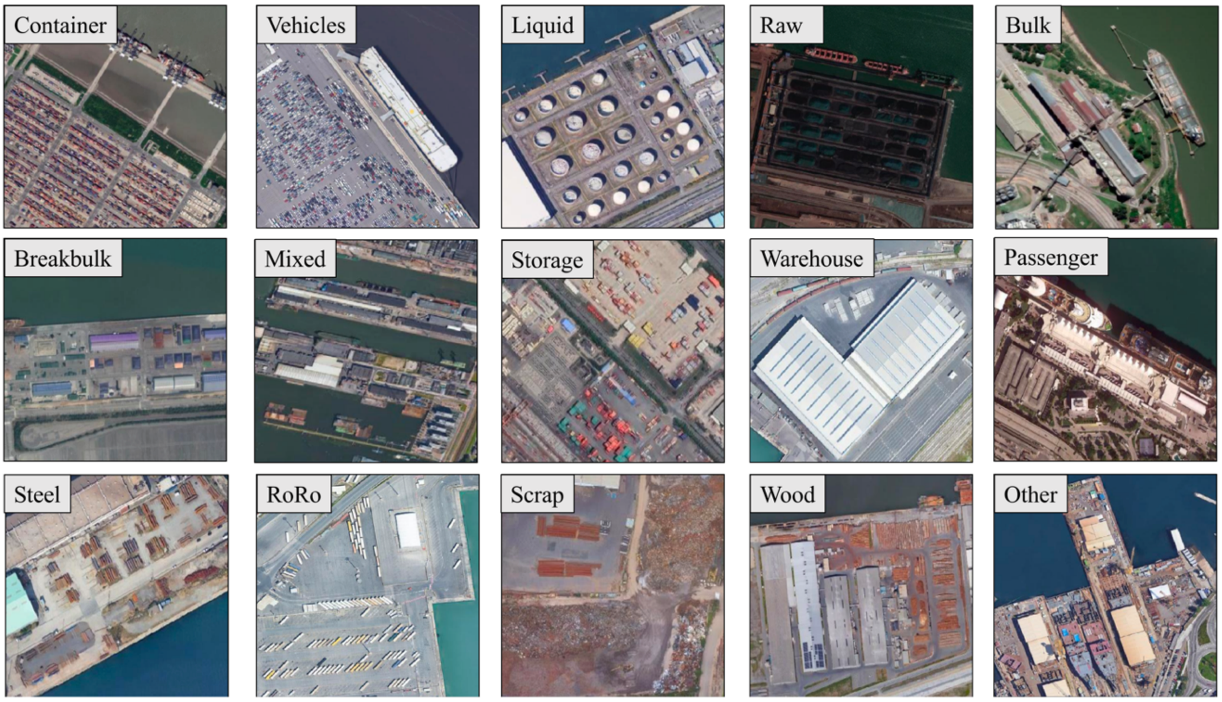
Supplementary Figure A3.1: The hazard exposure of ports. (a) The number of hazards that contribute to risk of a given port (median port-specific > 0) out of the six hazards considered (cyclone wind, coastal flooding, river flooding, pluvial flooding, earthquakes, operational). (b) A histogram of the fraction of ports exposed, grouped by the number of hazards for the median (black), 5th percentile (light blue, exposed if 5th percentile of port-specific > 0) and 95th percentile (green, exposed if 95th percentile of port-specific > 0) port-specific.



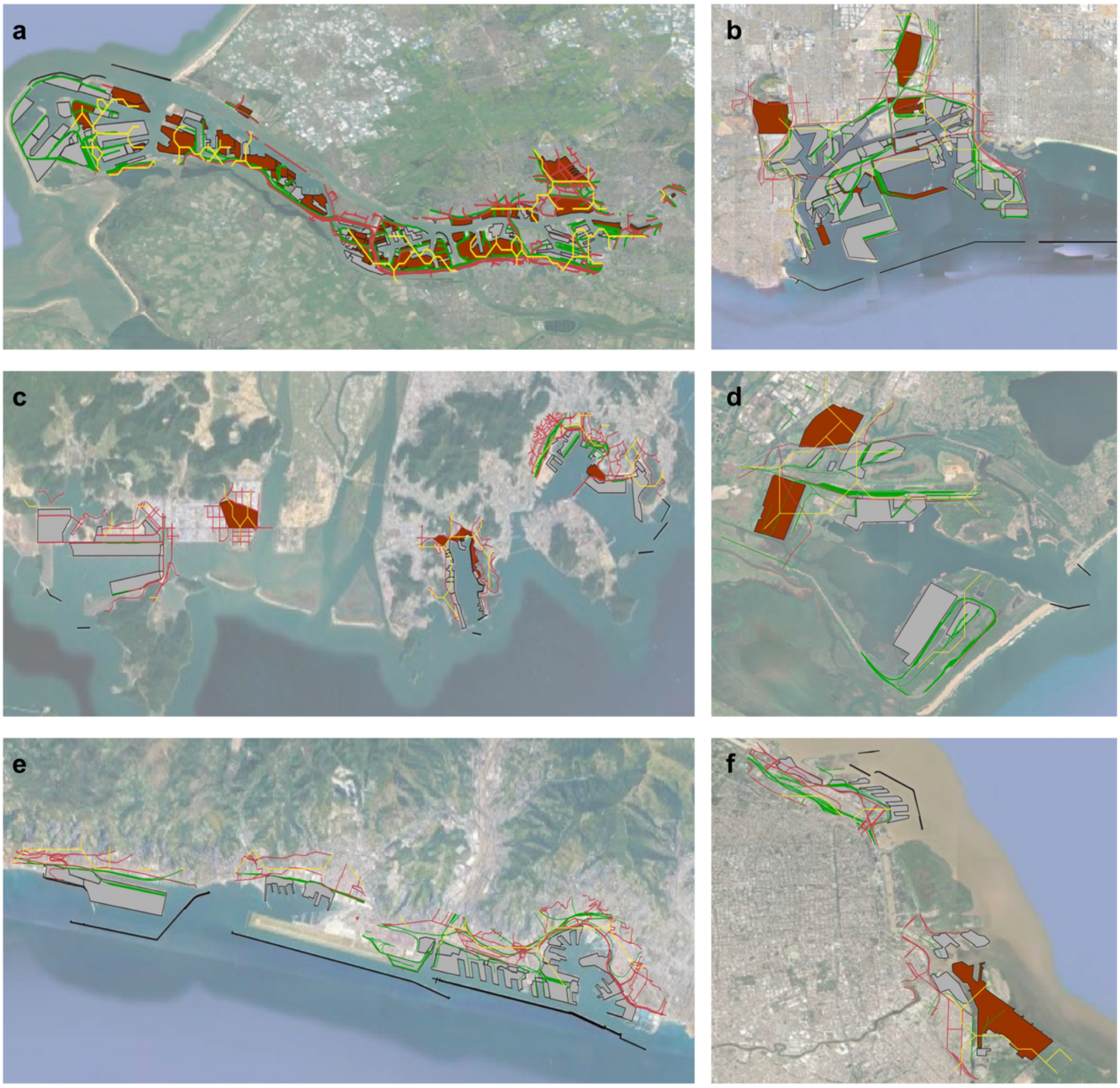
Supplementary Figure A3.2: The global footprint of port-specific per hazard. The size of the marker indicates the magnitude of port-specific, whereas the histogram shows the global aggregated port-specific across the 10,000 samples with the black line indicating the median and the dashed lines indicating the 5th and 95th percentile. Results are shown for Pluvial (a), Fluvial (b), Cyclone wind (c), Coastal (d), Earthquake (e) and Operational (f) hazard risk driver, respectively.



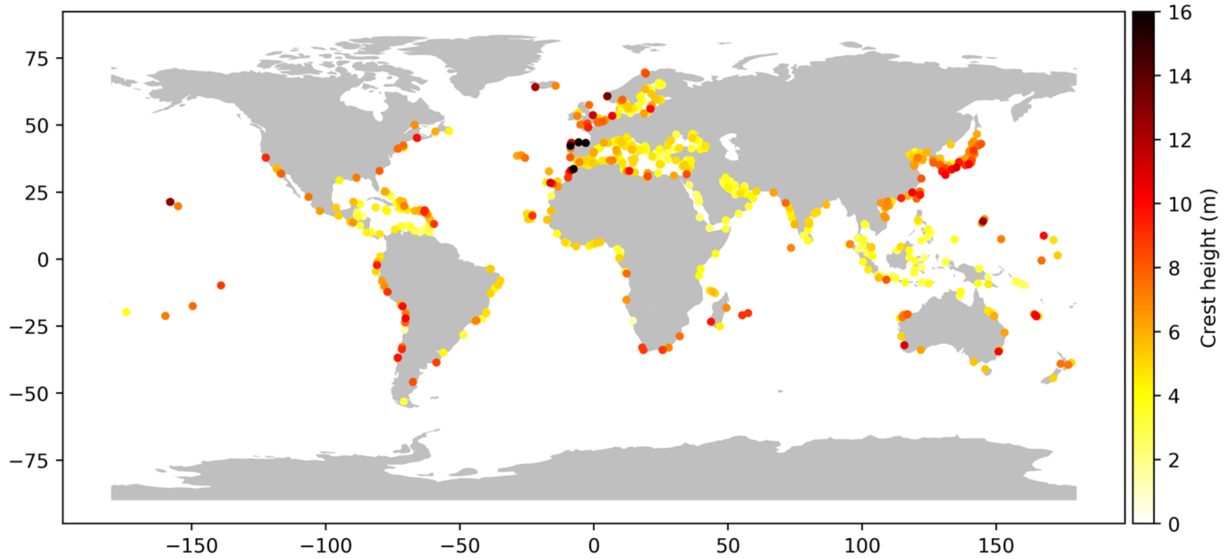
Supplementary Figure A3.3: Contribution of different hazard risk factors to the total port-specific by hazard type. (a) The absolute contribution to the median port-specific per hazard type. (b) Same as (a) but expressed in relative terms.



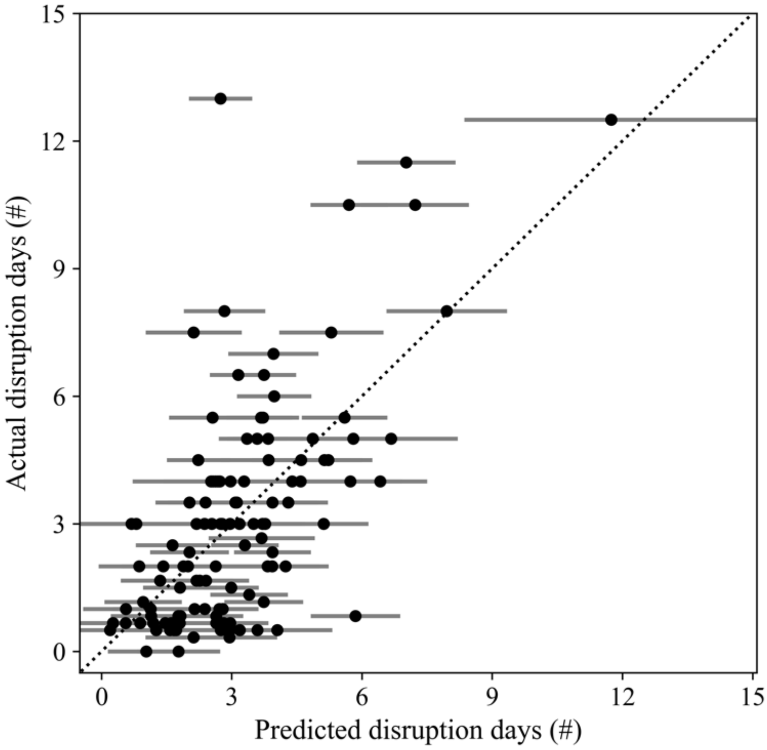
Supplementary Figure A3.4: The 15 different port land-use types considered in this study when mapping port areas.



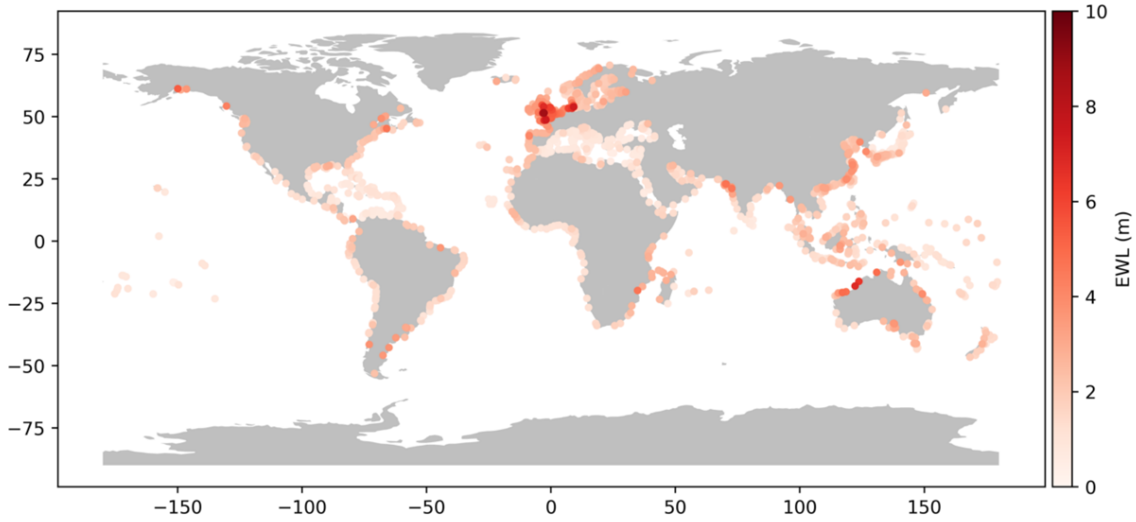
Supplementary Figure A3.5: Examples of port and critical infrastructure database for six ports. The figures show the port terminals (grey areas), industry (brown areas), roads (red lines), railway (green lines), electricity transmission (yellow lines) and breakwaters (black lines). The ports depicted are the port of Rotterdam (a), the ports of Los Angeles-Long Beach (b), the port of Busan (c), Richards Bay coal terminal (d), the port of Genoa (e) and the port of Buenos Aires (f).



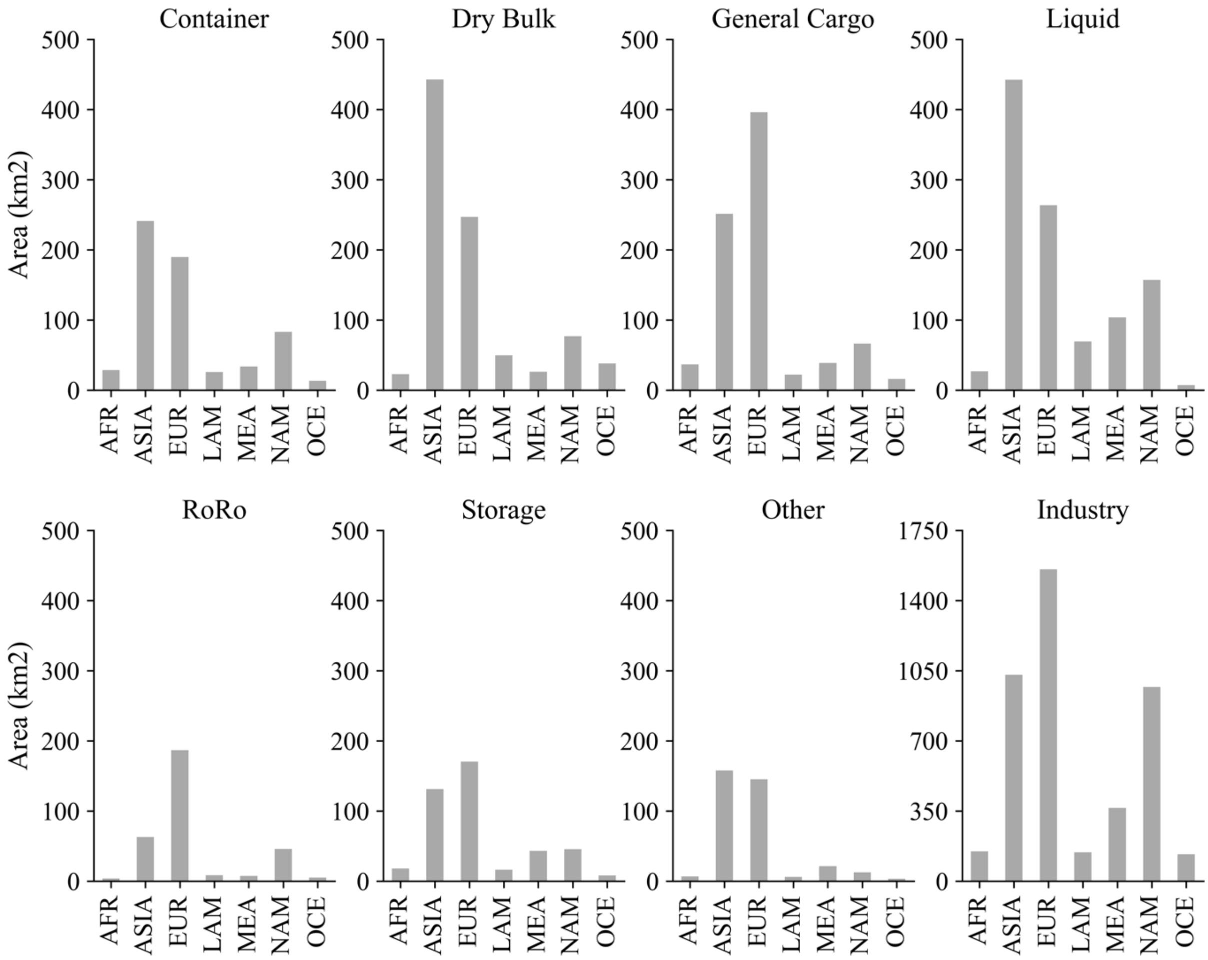
Supplementary Figure A3.6: The global distribution of breakwater crest heights modelled using the synthetic breakwater design methodology.



Supplementary Figure A3.7: The predicted versus observed number of disruption days of the cyclone-induced downtime regression model. The dot indicates the mean result of the regression whereas the error bar shows the 5-95th percentile of the regression model.



Supplementary Figure A3.8: The modelled 1-in-100 year extreme water level (EWL) at the port boundary used for the coastal flood risk modelling. Extreme water levels consist of storm surges, tides, sea-level anomalies and wave set-up for those ports that are exposed to wave set-up.



Supplementary Figure A3.9: The aggregated area of port infrastructure per region and land-use type, grouped into seven port land-use types (Container, Dry Bulk, General Cargo, Liquid, RoRo, Storage and Other, see Supplementary Table A3.2) and an industrial land-use type. Note the different y-axis scale of the Industry chart. AFR = Africa, ASIA = Asia, EUR = Europe, LAM = Latin America, MEA = Middle-East, NAM = North-America, OCE = Oceania.

Supplementary Tables

Supplementary Table A3.1**:** An overview of the model parameters used in this study and the adopted values. The lower and upper range of the values reflect the respective lower and upper range of the uniform distribution used in the sensitivity analysis. *Values are scaled from 1998 values to 2018 values using yearly inflation rates and converted from euro to dollar.

Category	**Parameter**	**Description**	**Value**	**Lower**	**Upper**	**Source**
Operational	Wave threshold	The wave height threshold used (m) (ME|HE)	4.0|5.0	3|4	5|6	Expert Judgment
	Temperature threshold	The temperature threshold used (Celsius) (Rest of world | Middle-East)	35|45	32|42	38|48	(Izaguirre *et al.*, 2021), Expert Judgment
	Wind speed threshold	The wind speed empirical function used	17	13	21	(Izaguirre *et al.*, 2021), Expert Judgment
	Overtopping threshold	The overtopping threshold used (l/s/m) (coastal breakwater | seawall)	1.0|0.4			(EurOtop, 2018)
	Breakwater design	The design breakwater conditions	1	0.5	1.5	Expert judgment
	Design wave height breakwater	The design wave height return period for breakwater design (years)	475	100	1000	Expert Judgment
Equipment	Number of cranes	Number of cranes on a container terminal per vessel	3	2	4	Scaling relationship
Cost scaling	Scaling factor Europe, North-America, Australia	The scaling factor applied for the port land-use damage values	1			Expert judgment, (World Bank, 2021)
	Scaling factor Africa	The scaling factor applied for the port land-use damage values	1.1			Expert judgment, (World Bank, 2021)
	Scaling factor Middle-East	The scaling factor applied for the port land-use damage values	0.6			Expert judgment, (World Bank, 2021)
	Scaling factor Asia	The scaling factor applied for the port land-use damage values	0.5			Expert judgment, (World Bank, 2021)
	Scaling factor South America, Caribbean, Pacific	The scaling factor applied for the port land-use damage values	0.8			Expert judgment, (World Bank, 2021)

Reconstruction costs	Maximum damage General cargo	Maximum damage value used in risk analysis (USD/m2)	1000*	700	1300	(Snuverink *et al.*, 1998), (World Bank, 2021)
Port land-use	Maximum damage RoRo	Maximum damage value used in risk analysis (USD/m2)	750*	500	1000	(15), (World Bank, 2021)
	Maximum damage Liquid	Maximum damage value used in risk analysis (USD/m2)	1000*	500	1500	(15), (World Bank, 2021)
	Maximum damage Container	Maximum damage value used in risk analysis (USD/m2)	800*	600	1000	(Snuverink *et al.*, 1998), (World Bank, 2021)
	Maximum damage Bulk	Maximum damage value used in risk analysis (USD/m2)	550*	400	700	(Snuverink *et al.*, 1998), (World Bank, 2021)
	Maximum damage Raw	Maximum damage value used in risk analysis (USD/m2)	550*	400	700	(Snuverink *et al.*, 1998), (World Bank, 2021)
	Maximum damage Refinery	Maximum damage value used in risk analysis (USD/m2)	1800*	1500	2100	(Snuverink *et al.*, 1998), (World Bank, 2021)
	Maximum damage Industry	Maximum damage value used in risk analysis (USD/m2)	400	300	500	(Huizinga, De Moel and Szewczyk, 2017)
	Maximum damage Warehouse	Maximum damage value used in risk analysis (USD/m2)	600	400	800	(ARE, 2018)
	Maximum damage Ship to Shore crane	Maximum damage value used in risk analysis (MUSD)	9	7	11	Expert Judgment, (Kox, 2016)
Reconstruction costs	Construction costs Road	Maximum damage value used in risk analysis (MUSD/km)	3	1.5	4.5	(van Ginkel *et al.*, 2020)
Infrastructure	Construction costs Rail	Maximum damage value used in risk analysis (MUSD/km)	17	14	20	(Attina *et al.*, 2018)
	Construction costs Transmission	Maximum damage value used in risk analysis (MUSD/km)	1.1	0.7	1.5	(Mason, Curry and Wilson, 2012; World Bank, 2021)
	Construction costs Power plant	Maximum damage value used in risk analysis (MUSD)	300	100	900	(FEMA, 2020a; World Bank, 2021)

	Ratio reconstruction/ construction costs	The ratio between reconstruction costs and total construction costs	0.6	0.5	0.7	Expert Judgment
Depth-damage curve	Uncertainty fragility flood	Uncertainty in the fragility curves adopted (m)	0	-0.5	0.5	Expert Judgment
Flooding	Fragility Breakbulk flooding	Fragility curve used in risk analysis				(Snuverink *et al.*, 1998)
	Fragility RoRo flooding	Fragility curve used in risk analysis				(Snuverink *et al.*, 1998)
	Fragility Raw flooding	Fragility curve used in risk analysis				(Snuverink *et al.*, 1998)
	Fragility Liquid flooding	Fragility curve used in risk analysis				(Snuverink *et al.*, 1998)
	Fragility Container flooding	Fragility curve used in risk analysis				(Snuverink *et al.*, 1998)
	Fragility Bulk flooding	Fragility curve used in risk analysis				(Snuverink *et al.*, 1998)
	Fragility Refinery flooding	Fragility curve used in risk analysis				(Snuverink *et al.*, 1998)
	Fragility Warehouse flooding	Fragility curve used in risk analysis				(Pitilakis *et al.*, 2019)
	Fragility Industry flooding	Fragility curve used in risk analysis				(Huizinga, De Moel and Szewczyk, 2017)
	Fragility Road/rail	Fragility curve used in risk analysis				(Koks *et al.*, 2019)
	Fragility Electricity	Fragility curve used in risk analysis	Unaffected			
	Fragility Power	Fragility curve used in risk analysis				(Miyamoto International, 2019)
Depth-damage curve	Uncertainty fragility earthquake	Uncertainty in the fragility curves adopted (PGA)	0	-0.2	0.2	Expert Judgment
Earthquake	Fragility Liquid earthquake	Fragility curve used in risk analysis				(Kaynia, 2013)
	Fragility Bulk earthquake	Fragility curve used in risk analysis				(Guo *et al.*, 2016)
	Fragility Warehouse earthquake	Fragility curve used in risk analysis				(Kaynia, 2013)

	Fragility Quay walls earthquake	Fragility curve used in risk analysis				(Na and Shinozuka, 2009)
	Fragility Road earthquake	Fragility curve used in risk analysis				(Argyroudis and Kaynia, 2014)
	Fragility Rail earthquake	Fragility curve used in risk analysis				(Kaynia, 2013))
	Fragility Electricity earthquake	Fragility curve used in risk analysis				(Miyamoto International, 2019)
	Fragility Power	Fragility curve used in risk analysis				(Miyamoto International, 2019)
Depth-damage curve	Uncertainty fragility TC	Uncertainty in the fragility curves adopted (m/s)	0	-10	10	Expert Judgment
Tropical cyclones	Fragility Liquid TC	Fragility curve used in risk analysis				(Kameshwar and Padgett, 2018)
	Fragility Bulk TC	Fragility curve used in risk analysis				(Kameshwar and Padgett, 2018)
	Fragility Warehouse TC	Fragility curve used in risk analysis				(Lee, Ham and Kim, 2013)
	Fragility Quay walls TC	Fragility curve used in risk analysis	Unaffected			
	Fragility Road TC	Fragility curve used in risk analysis	Unaffected			
	Fragility Rail TC	Fragility curve used in risk analysis	Unaffected			
	Fragility Electricity TC	Fragility curve used in risk analysis				
	Fragility Power TC	Fragility curve used in risk analysis				(Miyamoto International, 2019)

	Fragility Container crane TC	Fragility curve used in risk analysis				(Gur and Ray-Chaudhuri, 2014)
Recovery	Recovery duration flooding	Recovery curve used for damage essential port land use				Expert Judgment
Flooding	Uncertainty recovery curve	Uncertainty in the recovery curves adopted (%)	0	-10	10	Expert Judgment
	Maximum recovery port flooding	Maximum downtime when a port is flooded (#days)	120	90	150	Expert Judgment
	Maximum recovery road flooding	Maximum downtime when a road is flooded (#days)	45	30	60	Expert Judgment
	Maximum recovery rail flooding	Maximum downtime when a rail is flooded (#days)	45	30	60	Expert Judgment
	Maximum recovery power flooding	Maximum downtime when power is flooded (#days)	50	40	60	Expert Judgment
Recovery	Recovery duration earthquake	Recovery curve used for damage essential port land use				(FEMA, 2020b)
Earthquake	Uncertainty recovery curve	Uncertainty in the recovery curves adopted (%)	0	-10	10	Expert Judgment
	Maximum recovery port earthquake	Maximum downtime when a port is hit by earthquake (#days)	300	250	350	(FEMA, 2020b)
	Maximum recovery road earthquake	Maximum downtime when a road is hit by earthquake (#days)	90	60	120	(FEMA, 2020b)
	Maximum recovery rail earthquake	Maximum downtime when a rail is hit by earthquake (#days)	90	60	120	(FEMA, 2020b)
	Maximum recovery electricity earthquake	Maximum downtime when a transmission line is hit by earthquake (#days)	30	25	35	(FEMA, 2020b)
	Maximum recovery power earthquake	Maximum downtime when power plants is hit by earthquake (#days)	100	80	120	(FEMA, 2020b)

Recovery	Recovery duration TC	Duration downtime when a TC hits a port (#days)	Empirical			(Verschuur, Koks and Hall, 2020)
Tropical cyclones	Uncertainty recovery curve	Uncertainty in the recovery curves adopted (%)	0	-10	10	Expert Judgment
	Maximum recovery cranes TC	Maximum downtime when cranes are destroyed by TC (#days)	200	150	250	Expert Judgment
	Maximum recovery electricity TC	Maximum downtime when transmission lines are destroyed by TC (#days)	30	25	35	Expert Judgment
	Maximum recovery power plant TC	Maximum downtime when power plants are destroyed by TC (#days)	50	40	60	Expert Judgment
Logistics losses	Freight rate	Freight rate in USD per tonnes	1.0	0.5	1.5	(Y. Zhang *et al.*, 2020)
	Port charge	Port charge to load/unload freight in USD per tonnes	5.5	1.0	10.0	(Y. Zhang *et al.*, 2020)
	Inventory	Inventory costs to store freight in USD per tonnes	0.5	0.1	0.9	(Y. Zhang *et al.*, 2020)
	Value of time	Value of time for delay of goods in USD per tonnes per day	5.5	1.0	10.0	

Supplementary Table A3.2: The 15 types of port land-use types used in the port mapping exercise together with description and the group they belong to.

Subgroup	Group	Description
Container	Container	Dedicated terminal for the loading/offloading and storage of containers
Vehicles	RoRo	Dedicated terminal for the loading/offloading and storage of vehicles
Liquid	Liquid	Dedicated terminal for the loading/offloading and storage of oil and gas-related products
Raw	Dry Bulk	Open terminals for the loading/offloading and storage raw materials such as iron ore, coal, alumina, phosphate etc.
Bulk	Dry Bulk	Closed terminals (silos, warehouses) for the loading/offloading and storage of raw materials such as grains, cement etc.
Breakbulk	General Cargo	Breakbulk terminals and storage areas. Handling of cargo in unitized form such as pallets, bags, creates etc.
Mixed	General Cargo	A mix of various types, but predominantly breakbulk goods
Storage	Storage	A dedicated storage space located not part of the port terminals. Can be used for the storage of all type of goods (containers, breakbulk)
Warehouse	Storage	A warehouse used for the storage and distribution of goods
Passenger	Other	A passenger terminal used for mooring of passenger vessels, ferries and cruise ships
Steel	General Cargo	A dedicated terminal for the loading/offloading and storage of steel products
RoRo	RoRo	A roll on roll off terminal used for the movement of trucks on dedicated RoRo vessels
Scrap	General Cargo	A dedicated terminal for the loading/offloading and storage of scrap products
Wood	General Cargo	A dedicated terminal for the loading/offloading and storage of wood and paper products
Other	Other	Other land-use types not mentioned above. In particular shipyards and land under construction

Supplementary Table A3.3: A comparison of country-wide port areas (in km^2) across studies as presented in Table 3 of Hanson and Nicholls (2020) (Hanson and Nicholls, 2020). Columns 2-5 are directly adopted from Hanson and Nicholls (2020) (please refer to this study for details) whereas columns (6-8) are based on the port area mapping performed in this study as described above. 'All land-use' includes all land-use types, including 'Industry'. 'No industry' includes all port land-use types but not 'Industry'. 'Select land-use' includes all port-land use types (no industry), except land-use classified as 'Industry', 'Storage' or 'Other' (see Supplementary Table A3.2).

Country	**Hanson and Nicholls (2020)**	**Dronkers *et al.* (1990)**	**Lloyds List (2009)**	**AAPA (2014)**	**This study - all land-use**	**This study - no industry**	**This study - selected land-use**
Australia	63.84	75.6	65.22	98.94	145.99	53.33	47.16
Belgium	13.01	25.3	24.53	19.82	86.58	38.75	28.08
Bulgaria	1.59	9.7	0.55	1.22	3.13	2.27	1.71
China	171.77	26.8	406.63	547.42	764.01	614.87	514.80
Finland	6.41	12	6.97	3.21	53.66	26.36	22.71
France	19.78	44.7	31.29	25.35	122.27	53.26	41.41
Germany	29.33	38.1	32.88	26.5	82.13	45.10	34.88
Ireland	3.68	4.1	4.87	2.67	13.25	6.83	5.78
Italy	25.21	42.9	32.94	23.44	109.97	41.60	33.33
Japan	89.17	199.1	72.99	79.03	416.47	254.84	214.28
Netherlands	24.85	75.9	36.94	47.05	131.57	50.93	34.40
Poland	3.96	16.3	3.92	5.32	18.40	12.60	9.81
Romania	3.71	9.5	4.96	4.57	11.10	5.22	4.81
Spain	23.14	39.7	39.74	24.98	112.82	50.54	38.44
United Kingdom	32.79	64.4	38.05	19.79	113.52	56.54	47.10
United States	112.7	138.7	144.9	160.26	808.96	255.82	230.23
Total	624.94	822.8	947.38	1089.57	2993.83	1568.86	1308.93

Supplementary Table A3.4: Result of the variance-based sensitivity analysis for global aggregated economic and trade risk. The values indicate to what extent a parameter contribute to the variance of the results. The top-10 most important parameters are highlighted in bold.

Category	Variable	Port-specific risk	Trade risk
Operational	**Wave threshold**	**0.024**	**0.115**
	Temperature threshold	0.000	**0.038**
	Wind speed threshold	0.000	0.000
	Breakwater design	0.000	0.000
	Design wave height breakwater	0.000	0.000
Equipment	Number of cranes	0.001	0.000
Reconstruction costs	**Maximum damage General cargo**	**0.005**	0.000
	Maximum damage RoRo	0.000	0.000
	Maximum damage Liquid	0.000	0.000
	Maximum damage Container	0.002	0.000
	Maximum damage Bulk	0.000	0.000
	Maximum damage Raw	0.000	0.000
	Maximum damage Refinery	0.000	0.000
	Maximum damage Industry	**0.004**	0.000
	Maximum damage Warehouse	0.000	0.000
	Maximum damage Ship to Shore crane	0.000	0.000
	Construction costs Road	0.000	0.000
	Construction costs Rail	**0.003**	0.000
	Construction costs Transmission	0.000	0.000
	Construction costs Power plant	0.000	0.000
	Ratio reconstruction/ construction costs	**0.002**	0.000
Depth-damage curve	**Uncertainty fragility flood**	**0.060**	**0.016**
	Uncertainty fragility cyclone	**0.929**	**0.772**
	Uncertainty fragility earthquake	**0.006**	**0.002**
Recovery	**Recovery duration flooding**	0.000	**0.022**
	Recovery duration cyclone	**0.010**	**0.027**
	Recovery duration earthquake	0.000	0.000
	Maximum recovery port flooding	0.000	0.000

	Maximum recovery road flooding	0.000	0.000
	Maximum recovery rail flooding	0.000	0.000
	Maximum recovery power flooding	0.000	**0.002**
	Maximum recovery port earthquake	0.000	**0.000**
	Maximum recovery road earthquake	0.000	0.000
	Maximum recovery rail earthquake	0.000	0.000
	Maximum recovery electricity earthquake	0.000	0.000
	Maximum recovery power earthquake	0.000	0.000
	Recovery duration TC	0.001	**0.009**
	Maximum recovery cranes TC	0.000	0.000
	Maximum recovery electricity TC	0.000	0.000
	Maximum recovery power plant TC	0.000	0.000
Logistics losses	Freight rate	0.001	0.000
	Port charge	0.000	0.000
	Inventory	0.000	0.000
	Value of time	**0.029**	0.000

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APPENDIX 4: SUPPLEMENTARY INFORMATION 'CLIMATE RISKS TO PORT INFRASTRUCTURE EXPANSIONS FOR FUTURE GLOBAL TRADE'

Contains:

Supplementary Note A4.1-2

Supplementary Figure A4.1-13

Supplementary Table A4.1-5

Supplementary Note A4.1: Port planning and cost model

The area of a port can be divided in the total terminal area (A_{tot}) and the gross terminal area (A_{gr}). The gross terminal area only includes the stacks and internal infrastructure of the storage area, while the total terminal area covers the total landside (e.g. gross terminal area, buildings) and seaside areas (e.g. apron).

The investment cost of a port terminal refers to the greenfield cost of the terminal only, ignoring costs associated with supporting infrastructure (e.g. roads, rail, electricity), and the construction of breakwaters. We can distinguish between the total direct costs (C_{dir}) (sometimes referred to as base costs), which include the labour, equipment and materials needed to construct the terminal and the construction costs (C_{con}), which also include allowances (15%), indirect costs (25%), and contingencies (20%). In line with common practise, we assume:

$$C_{con} = 1.7 * C_{dir}$$

Below we describe how C_{dir} and A_{tot} are estimated per terminal type. The investment costs in the main manuscript all refer to the C_{con}. We use cost scaling factors per region to reflect broad-scale differences in construction costs (Supplementary Table A4.1). These cost ratios are derived in earlier work (Verschuur *et al.*, 2022) (Chapter 6).

Container terminal

Area requirement

The container terminal storage area is predicted using the following formula:

$$A_{tot} = \alpha_C * \frac{T * t * A_{TEU}}{V_{TEU} * r * m * 365}$$

With α_C the terminal conversion factor for container terminal (the conversion from storage to gross terminal area), T the throughput in tonnes per year, t the dwell time, A_{teu} the gross storage density of containers, r the ratio of average over maximum stacking height, m the storage occupancy ratio, and V_{teu} the tonnes to TEU conversion factor. A_{teu} and r depend on the equipment used in the storage yard (reach stacker, straddle carrier, gantry crane), see Supplementary Table A4.4 for the general ranges. Transhipment ports often have smaller space requirement, because of lower dwell times and lower values of α_C. Hence, we adopt the following formula:

$$A_{tot} = f_T * 0.5 * A_{tot} + (1 - f_T) * A_{tot}$$

With f_T the fraction of throughput that is transhipment. T and f_T come from the Oxford Maritime Transport model output, while for the other parameters we use a range of values from the literature (see Supplementary Table A4.2). For the construction of new container terminals, we use Rubble Tyred Gantry (RTG) cranes as main yard equipment type, since this is the most common equipment type across modern container ports, in particular for larger ports which handle the majority of containers (and where most port expansions will take place) (Wiese *et al.*, 2009).

Cost

The cost of a container terminal consists of the costs of the quay wall, the pavement, yard, container cranes, and yard equipment.

We can write the total costs as:

$$C_{dir} = L_{q,c} * C_{quay}(H) + A_{gr} * C_{yard} + L_{q,c}/n_{crane} * C_{crane} + 1.2\left(L_{q,c}/n_{yard,eq} * C_{yard,eq}\right) + 0.5 * C_{dredge} * A_{gr} * H * F_{dredge}$$

With $L_{q,c}$ the length of the quay, C_{quay} the construction costs of the quay as a function of the retaining height (H), C_{yard} the cost of the yard, n_{crane} the number of ship-to-shore cranes per quay length, C_{crane} the costs per ship-to-shore crane, $n_{yard,eq}$ the amount of main yard equipment per quay length, $C_{yard,eq}$ the cost of the yard equipment, C_{dredge} the cost of dredge materials for the landfill, and F_{dredge} the fraction of the hypothetical landfill that needs to be filled. The factor 1.2 covers that other yard equipment (e.g. side lifter, chassis) are ~20% of the main yard equipment costs.

The cost of the quay wall depends critically on the retaining height of the quay wall (i.e. the depth of the wall and sheet piles). To estimate the costs of the quay wall per running metre of quay, we use the formula of de Gijt (J.G. de Gijt, 2011) that is based on an analysis of a large number of quay walls globally, which is corrected from 2008 Euros to 2015 USD:

$$C_{quay}(H) = 1130\, H^{1.2729}$$

With *H* the retaining height. The retaining height depends on the design draft (d_{design}) of the largest vessel that calls at the port (which determines the freeboard and design water depth). Here, we assume that the retaining height is equal to 1.8 to 2.5 times the design draft (H_{ratio}) of the vessel in line with Kox (2016) and as mentioned in (OECD-ITF, 2015).

$$H = H_{ratio} * d_{design}$$

The design draft of the largest vessel is estimated per port based on Automatic Identification System (AIS) data for 2019 – 2020 as derived in previous work (Verschuur, Koks and Hall, 2021a).

The length of the quay ($L_{q,c}$) depends on the number of container handled per year. Based on data in Wiese *et al* (Wiese *et al.*, 2009), we find this relationship ($R^2 = 0.92$) to be:

$$L_{q,c} = 0.62\ (\text{TEU}/1000)$$

With *TEU* the number of TEUs handled, which is derived by dividing T/C_{TEU}

The yard costs (C_{yard}) are derived from Becker *et al*. (Becker, Hippe and Mclean, 2017), who estimate the yard costs (which include pavement, warehouse, unpaved areas, buildings) to be 100 - 153 USD/m^2.

The number of ship-to-shore cranes depends on the length of the berth. Based on data in Wiese *et al*. (Wiese *et al.*, 2009) we find approximately one crane per 80 – 120 metre quay length at a cost of approximately 7 - 11 million USD per crane. For the yard equipment, one uses approximately 1 RTG per 40-60 m quay wall at a cost of 1 - 2 USD million per RTG.

The cost of land reclamation is related to the volume to be filled, assumed to be half of the gross area times the retaining depth (i.e. half because it is assumed that the original land has a sloping side), and the cost of dredging suitable materials (C_{dredge}). The cost of the landfill material depends a lot on the availability of suitable materials (e.g. imported or locally available) and the costs to extract and transport it. The cost range can therefore be large, and based on different unit costs found in the literature (Becker, Hippe and Mclean, 2017), we set this value to 10 – 25 USD/m^3. Supplementary Table A4.3 provides an overview of all parameters.

RoRo terminal

Area requirement

There are no general guidelines for the design of RoRo terminals. Therefore, we use the terminal area and throughput dataset to come up with a suitable scaling factor (Supplementary Note 2). We find a global average value of 4.1 tonnes/m^2, with a 25-75% uncertainty (for 66 ports) of 1.5 to 9.7 tonnes/m^2. We therefore model this using a triangular distribution function to sample possible tonnes-to-area conversion values.

Cost

The total cost of a RoRo terminal consists of the costs of the quay wall and the yard pavement. Equipment is not considered for RoRo terminals, as little landside equipment is required. The costs can be written as

$$C_{dir} = A_{gr} * R_a * C_{quay}(H) + A_{gr} * C_{pav} + 0.5 * C_{dredge} * A_{gr} * H * F_{dredge}$$

With R_a the quay wall length to storage area ratio and C_{pav} the pavement costs of heavy duty pavement including buried service infrastructure.

Based on the design of existing RoRo terminals as described in HPA (2017) (Hamburg Port Authority, 2017), R_a is found to be around 0.001 – 0.005 m/m^2, and the C_{pav} around 150 – 250 USD/m^2.

General cargo terminal

Area requirement

The general cargo storage area can be predicted using the following formula:

$$A_{tot} = \alpha_{GC} * \frac{T * t * f_{area} * f_{bulk}}{h_s * m * \rho_{cargo} * 365}$$

With f_{area} the area factor of bulk, f_{bulk} the bulk factor, h_s the average stacking height, and ρ_{cargo} the average density of cargo. We use a range of values from the literature (see Supplementary Table A4.2).

Cost

The total cost of a general cargo terminal consists of the costs of the quay wall, equipment and pavement:

$$C_{dir} = 1.2\ (A_{gr} * R_a * C_{quay}(H) + A_{gr} * C_{pav})\ + 0.5 * C_{dredge} * A_{gr} * H\ * F_{dredge}$$

To estimate the quay length, we use R_a values of 0.001 - 0.005 m/m^2, which are common values found for a range of general cargo terminals across geographies (Hamburg Port Authority, 2017), and pavements costs of 150 - 250 USD/m^2. The equipment costs are very much dependent on the type of general cargo terminal (e.g. types of goods, storage requirement). Here, we assume equipment costs to be 20% of the costs of quay walls and pavement. See Supplementary Table A4.3 for all details.

Liquid bulk terminal

Area requirement

The liquid bulk storage area can be predicted using the following formula:

$$A_{tot} = \alpha_L * \frac{T * t}{V_{area} * m * \rho_{cargo} * 365}$$

With V_{area} the storage area of a volume of goods (m^3/m^2). We use a range of values from the literature (see Supplementary Table A4.2).

Cost

In comparison with the other terminals, liquid bulk terminal often use jetties for berthing (instead of a quay wall) and do not require (or require small amounts of) pavement. The total costs cover the costs of storage tanks (~50% of construction costs (Kox, 2016)), jetties, pipelines, and bunds. Estimating the costs of the individual components is difficult. Instead we use the unit storage costs (*Sc*), in terms of USD per storage volume (USD/m^3), which range between 350 – 700 USD/m^3 as found in the literature (Kox, 2016; ERIA, 2018). In short, we can write:

$$C_{dir} = \frac{T * t}{\rho_{cargo} * 365} * Sc$$

Details of the parameters are included in Supplementary Table A4.3.

Dry bulk terminal

Area requirement

The liquid bulk storage area can be predicted using the following formula:

$$A_{tot} = \alpha_L * \frac{T * t * f_{area}}{hs * m * \rho_{cargo} * 365}$$

We calculate this separately for cargo that is stored in silos (e.g. grains, cement) and cargo stored in stockpiles (e.g. iron ore, coal), either open or with a shed around it. Some correction factors apply. Export terminals of iron ore/coal have 50% lower storage factors than importing terminals, and the area requirement of silos is around a third of the area requirement of an open storage (Kox, 2016). We therefore estimate the total bulk area requirement for a port to be:

$$A_{tot} = f_{silo} * 1/3 * A_{tot,s} + (1 - f_{silo}) * (f_{export} * A_{tot,o} * 0.5 + \left(1 - f_{export}\right) * A_{tot,o})$$

With $A_{tot,s}$ the area derived for cargo in silos (e.g. grains) , $A_{tot,o}$ the area derived for cargo in open storage (e.g. coal), f_{silo} the fraction of bulk that will likely be stored in silos and f_{export} the fraction of throughput that is export. We estimate f_{silo} as the fraction of agricultural bulk trade (silos) compared to the total bulk trade, which includes both agricultural bulk trade and mining bulk trade. T, f_{silo} and f_{export} come from the Oxford Maritime Transport model output while for other parameters we use a range of values from the literature (see Supplementary Table A4.2).

Cost

The cost of a dry bulk terminal consists of the costs of the quay wall, storage facilities, pavement (if used) and equipment. The costs of silos and open storage differ and we therefore treat them separately. There are no common planning tools for silos. Instead, we directly adopt unit cost values expressed as the cost per tonnes goods handled (C_{silo}):

$$C_{dir,silo} = T * C_{silo}$$

C_{silo} is based on the unit costs of six grain terminals globally, which we estimate to be 15-25 USD/tonnes (see Supplementary Note 2).

For open storage terminals, planning tools do exist. The costs can be written as:

$$C_{dir,open} = L_{q,b} * C_{quay}(H) + A_{gr} * C_{pav} + C_{eq,b} + 0.5 * C_{dredge} * A_{gr} * H * F_{dredge}$$

With $L_{q,b}$ the length of the quay and $C_{eq,b}$ the costs of the equipment. The length can be derived by multiplying the annual throughput with the quay length factor (QLF):

$$L_{q,b} = \mathrm{T}/\ \mathrm{QLF}$$

A comparison of bulk terminals globally found that the QLF varies between 10,000 - 30,000 t/m for import terminals and 25,000 - 75,000 t/m for export terminals (van Vianen, 2015).

The cost of the equipment depends on the installed capacity of the equipment (in tonnes/hour), which is often several factors higher than the minimum capacity (T / $(24*365)$). According to van Vianen (van Vianen, 2015) the total equipment costs of bulk terminals can be written as:

$$C_{eq,b} = \mathrm{M_c} * \ (0.077 * \mathrm{I_{eq}}\ (\mathrm{T}/\ (24 * 365)))$$

With M_c the investment of machinery as a function of weight and I_{eq} the installed capacity of the equipment. According to van Vianen *et al.* (van Vianen, Ottjes and Lodewijks, 2011), M_c is between 7000 - 9000 USD/kg, and I_{eq} is 14.5 - 26.5 times the minimum capacity for import terminals and 7.6 – 13 times the minimum capacity for export terminals.

We can therefore estimate the total cost of bulk terminals using the fraction of bulk being stored in silos and open storage:

$$C_{dir} = C_{dir,silo} * f_{silo} + C_{dir,open} * (1 - f_{silo})$$

Details of all parameters are included in Supplementary Table A4.3.

Supplementary Note A4.2: External validation PPC model

As external validation, we compare the model output with various external data sources covering both the unit area requirement (tonnes per m^2) and the unit construction cost (USD per tonnes).

Unit area requirement

In terms of unit area requirement, we compare our results with two sources. First, we collate general rules of thumb reported in the literature. Second, we derive empirical tonnes to area ratios by combining terminal-specific port capacity estimates for around 200 ports globally, obtained from the ITF-OECD (ITF, 2015), with the manually mapped gross terminal area of these ports, as done in (Verschuur *et al.*, 2022) (Chapter 6) (henceforth 'externally estimated ratios'). The results are summarised in Supplementary Table A4.5 per terminal type. We report the median values and 10 – 90^{th} percentiles in brackets.

For container terminals, the modelled values depend on the type of main yard equipment adopted. The PPC model predicts values of 17.3 (11.0-27.0) tonnes/m^2 for RTG cranes, 19.8 (13.7 - 29.0) tonnes/m^2 for RMG cranes, 10.9 (6.9 – 17.1) tonnes/m^2 for straddle carriers and 5.9 (3.7 – 9.1) tonnes/m^2 for reach handlers. This within the range of values based on the rules of thumb from the literature and the externally estimated ratios, which are mainly for larger container terminals that use RTG and RMG equipment. However, as suggested by Drewry (2010) (Drewry, 2010), there is a stark geographical divide in area needs, and it is not feasible to include all these nuances in our PPC model.

For general cargo terminals, the PPC predicts a value of 7.5 (4.7 - 11.6) tonnes/m^2, which is within the range of values based on the rules of thumb from the literature and the externally estimated ratios. It should be noted that the area requirement critically depends on the density of the cargo and the way it can be stored, which can vary widely between terminals. We have therefore used ratios that are quite general instead of modelling the space requirement for specialised general cargo terminals (e.g. steel, wood).

For liquid bulk terminals, the unit area requirement we find is 33.1 (20.8 - 53.7) tonnes/m^2. This is in line with the rules of thumb for oil and LNG terminals, which both have slightly different design requirements. Our model is based on oil terminal design requirements as this is the dominant liquid bulk terminal type. Our values are higher than found using the externally estimated ratios, which is mainly because the externally mapped areas include areas beyond the storage area alone, such as refineries/processing plants, which can increase the size of the terminal considerably.

For dry bulk terminals, the PPC predicts a value of 19.4 (11.0 – 35.1) tonnes/m^2 for bulk stored in silos and 17.7 (9.8 – 34.3) tonnes/m^2 for open storage of raw material goods. These values are in line with the range of values based on the rules of thumb from the literature and the externally estimated ratios. However, bulk terminal space requirements differ widely between import and export terminals, which we tried to capture in the PPC model as well.

For RoRo terminals, we directly used the values of the externally estimated ratios in the model. This aligns well with values found for five new RoRo projects at the port of Tilbury (1.5 tonnes/m^2), Brunswick (0.7 tonnes/m^2), Mobile (1.3 tonnes/m^2), Melbourne (4.2 tonnes/m^2) and Port Said (5.2 tonnes/m^2).

Unit construction cost

In terms of unit construction costs (median and 10 – 90th percentile confidence interval), we compare our unit cost estimates to several external data sources collected. The PPC model estimates container ports to be around 420 (310 – 594) USD per TEU across all ports. A sample of 15 ports financed by the IFC captured within the World Bank's PPI database (World Bank, 2021) provides an average value of 450 USD per TEU, but with a range between 220 USD per TEU and 652 USD per TEU. The Asian Development Bank sets a value of 300 USD per TEU for ports in Asia to predict infrastructure investment needs (Asian Development Bank, 2017), while we estimate the value across Asia countries to be 348 (241 – 524) USD per TEU. Hence, differences are small between the PPC model output and reported container terminal construction costs.

An overview of 11 LNG terminals in Japan reported an average unit construction cost of 42.6 USD per tonnes (ERIA, 2018). For liquid bulk terminals, the PPC model estimates to be around 38.4 (23.9 – 58.4) USD per tonnes in Japan. LNG terminals are likely at the upper end of this range as they are generally more expensive compared to oil terminals (per tonnes throughput).

We estimate the unit construction costs of RoRo terminals to be 160.6 (99 – 281) USD per tonnes. The construction costs of three recently completed RoRo terminals are found to be 300 USD per tonnes (port of Tilbury), 200 USD per tonnes (port of Mobile), and 133 USD per tonnes (port of Port Said).

As mentioned in Supplementary Note 1, the unit costs of grain terminals are directly based on observed port construction projects at the ports of Varna (25 USD per tonnes), Yuzhny (21 USD per tonnes), Yanbu (22 USD per tonnes), Pivdenny (17 USD per tonnes) and Quequen (32.5 USD per tonnes).

Supplementary Note A4.3: Future climate change projections

We use different methodologies and data input to predict the changes in hazard occurrence under the three climate scenarios considered (RCP2.6, RCP4.5, RCP8.5). The methodology for estimating present day climate risks is explained in previous work (Verschuur *et al.*, 2022) (Chapter 6). Earthquakes are assumed to be unrelated to climate change and will remain constant over time.

In short, tropical cyclone wind, we use the expected change in extreme wind speed to derive new risk estimates. For fluvial flooding, coastal flooding and fluvial flooding, we use climate change scaling factors (CC scaling factors), that capture how the present-day return period will change in the future (e.g. the current 1-in-100 year event will become an 1-in-50 year event in the future). This allows us to re-run the risk calculations as outlined in (Verschuur *et al.*, 2022) (Chapter 6). For the operational thresholds, we evaluate the average yearly number of days that operations thresholds are exceeded. These thresholds are specified in for waves, wind, overtopping and temperature. We do not evaluate changes in extreme waves given that climate models are not able to capture wave dynamics properly, alongside the large uncertainties associated with global wave projections (Morim *et al.*, 2019).

Tropical cyclone wind

We use predicted extreme wind speed changes per cyclone basin from Knutson *et al*. (2020), and apply these percentage changes to the maximum wind speed for all return periods derived previously. This does not take into consideration that the frequency of extremes might decrease in the future, as is predicted for some regions (Knutson *et al*. 2020), as there is a lack of consistent information to include this effect.

Pluvial flooding

The current pluvial flood hazard maps are based on global hydrological model output, which are provided by JBA Consulting for six return periods. Here, we use precipitation projections from CMIP6 models to scale the return periods of pluvial flooding. For every CMIP6 model considered (22 in total), we evaluate per port the change in the daily extreme precipitation in the future (2035 – 2065) compared to the historical baseline (1979 – 2018). We estimate the return periods using a GEV function and look at the changes in return periods. We use the multi-model median CC scaling factor per port to derive the new return periods.

Fluvial flooding

The current fluvial flood hazard maps are based on global hydrological model output and a flood routing model, which are provided by JBA consulting for six return periods. To derive the CC scaling factor, we use the discharge output of six hydrological models (Jules-W1, CLM45, H08, LPJML, Orchidee, Watergap2) that are forced by four climate models (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5a-LR, MIROC5), as included in the 'Inter-Sectoral Impact Model Inter-comparison Project (ISIMIP2a)'. Please refer to earlier work for details and model evaluation (Hattermann *et al.*, 2018; Zaherpour *et al.*, 2018). We compare historical discharge time series (1981-2020) with future time series (2031-2060) at every port and estimate the CC scaling factors by extracting the monthly maxima and fitting a Gumbel distribution to both the present and future time series. We use the multi-model median CC scaling factor per port to derive the new return periods.

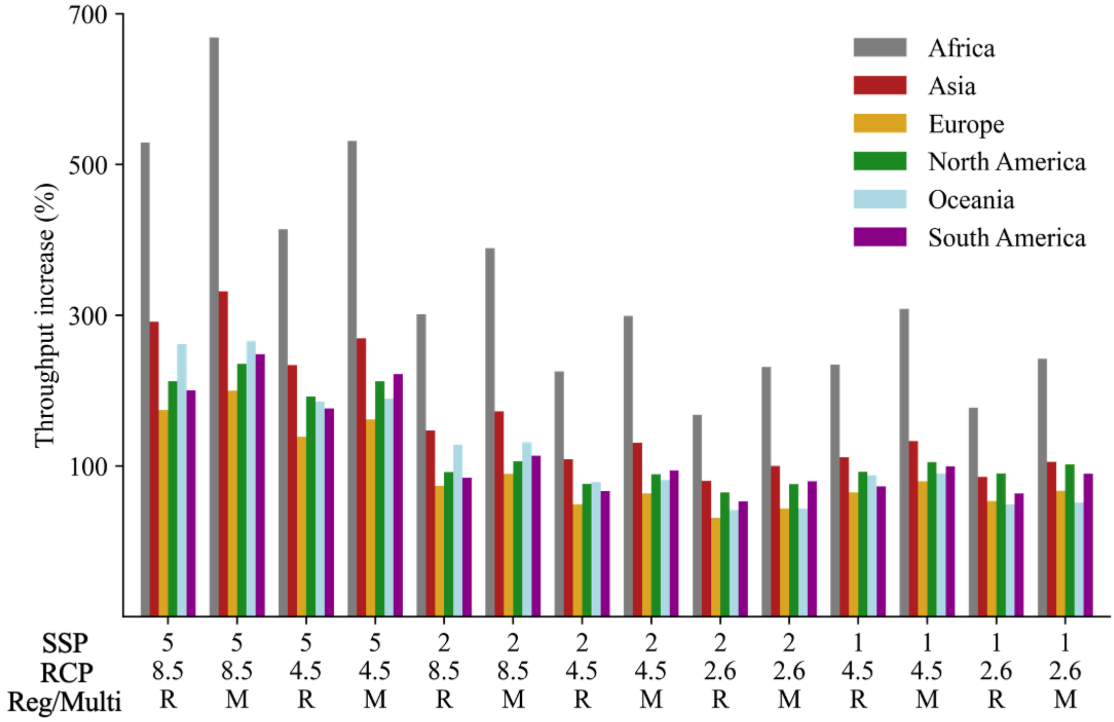
Coastal flooding

Coastal flood risk is estimated by the construction a number of return periods of an extreme water level (EWL) time series at every port and overlaying the EWL with a global digital elevation model for these number of return periods (see for details). Here, we use sea-level rise projections from Jackson and Jevrejeva (2016) (Jackson and Jevrejeva, 2016) to create future EWL time series. The sea-level rise projections predict the regional sea-level rise changes for in the future compared to the historical period (1986 – 2005). We first correct the projections such that 2015 is the base year, and fit a GEV to the historical and future time series to analyse the change in occurrence of the EWLs and derive the CC scaling factors.

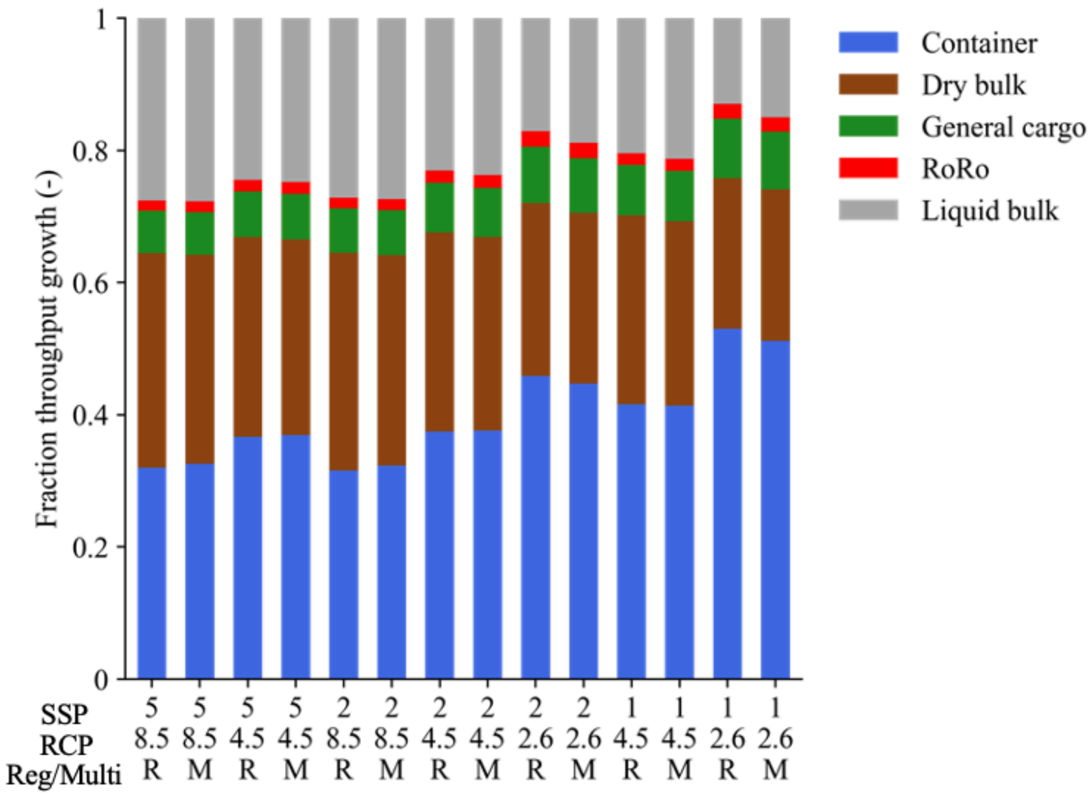
Operational thresholds

The baseline exceedance of wind, waves, overtopping and temperature are based on ERA5 reanalysis data. To project the operational exceedances of wind and temperature into the future, we derive, per port, the quantile the threshold corresponds in the reanalysis data and use the 22 CMIP6 climate models to project the changes in the exceedance of this quantile in the future (2035 – 2065). We use the change in threshold exceedance to estimate the future downtime risk (average expected number of days per year). To derive future overtopping exceedance, we apply sea-level rise scenarios for 2050 based on Jackson and Jevrejeva (2016) (Jackson and Jevrejeva, 2016) to the modelled present-day overtopping discharges (which changes the storm surge in front of the breakwater or quay wall), and re-evaluate the number of times the overtopping discharges exceed the operational threshold set.

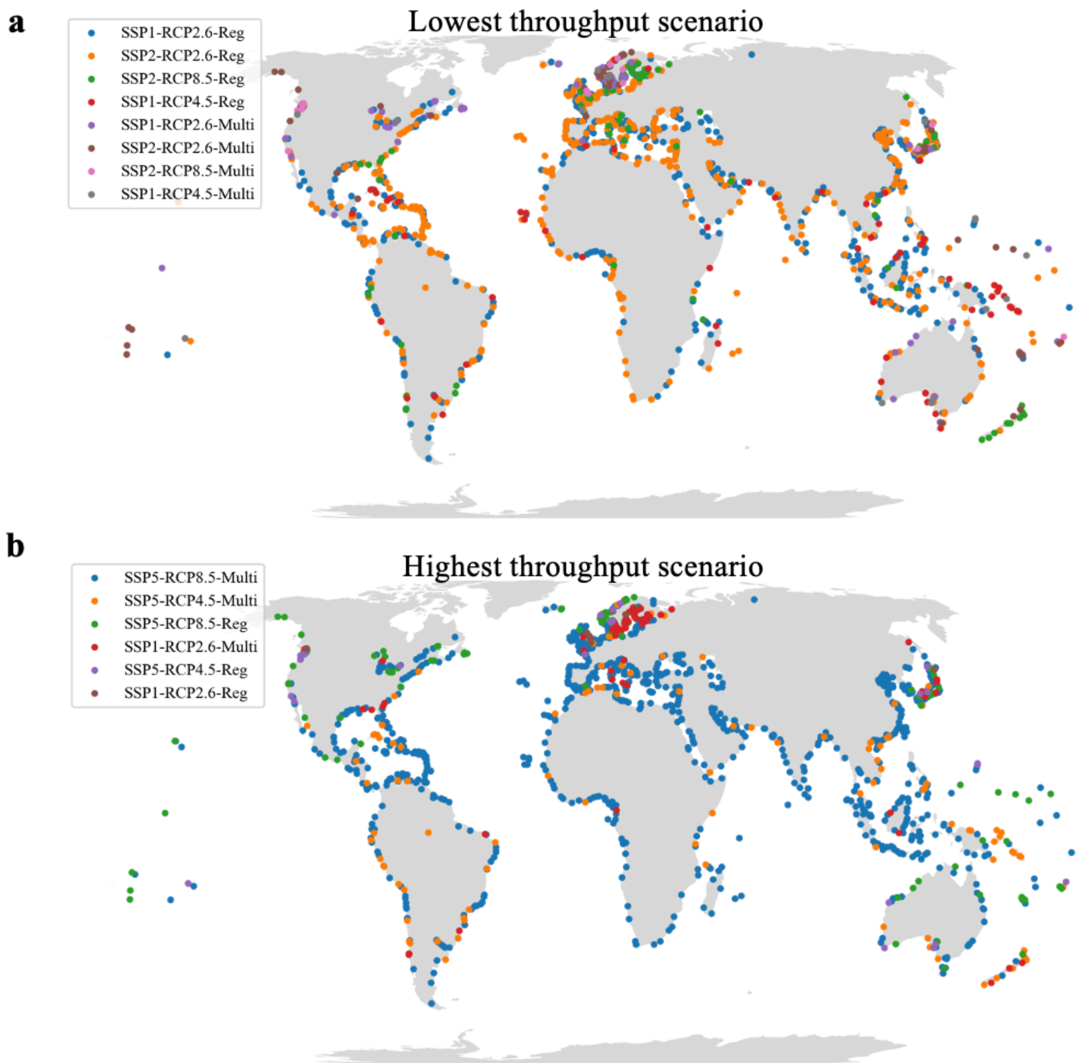
Supplementary Figures



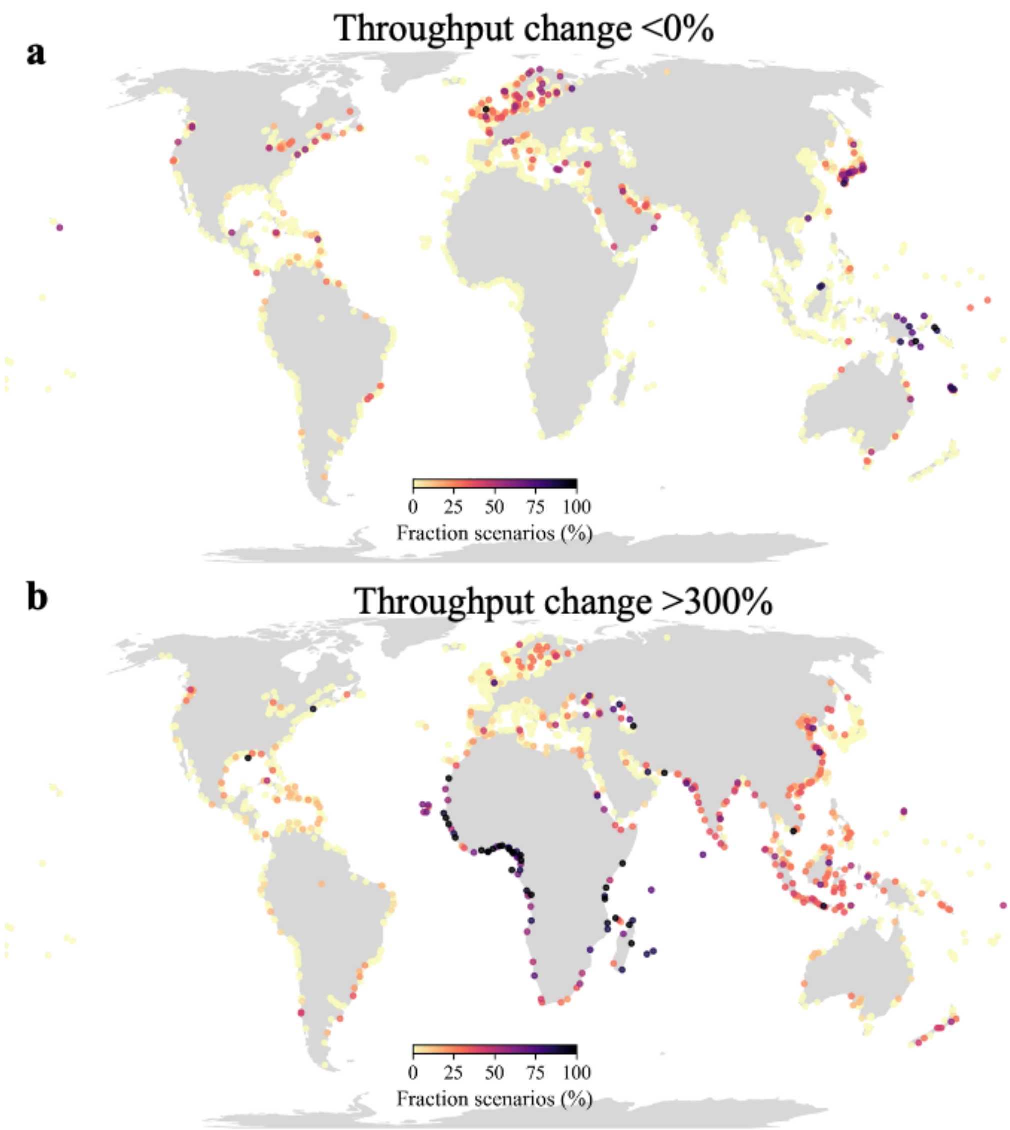
Supplementary Figure A4.1: Throughput growth per continent. Change in global throughput in 2050 compared to the 2015 per continent and trade scenario.



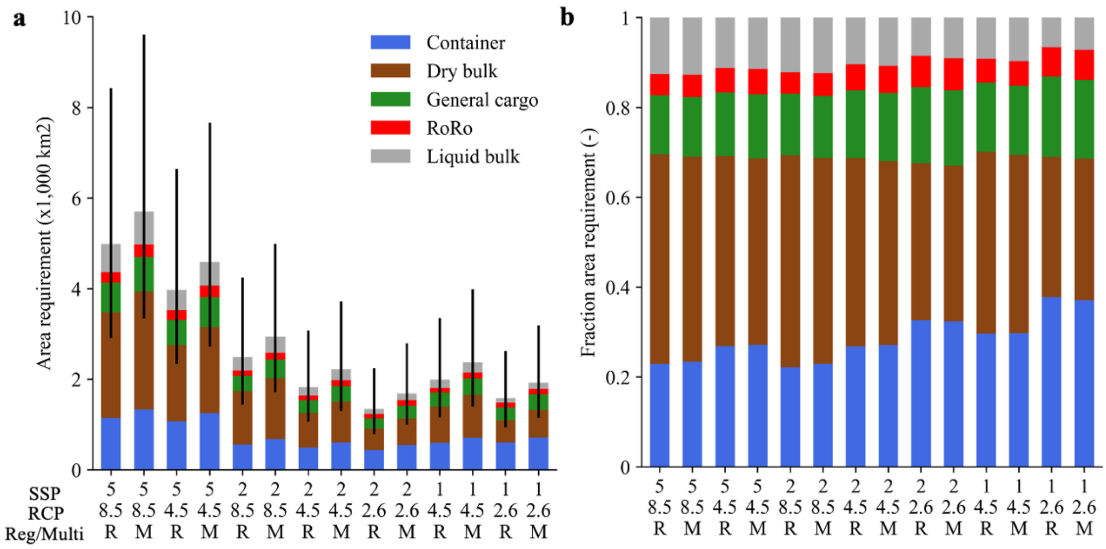
Supplementary Figure A4.2: Contribution throughput growth per terminal type. The relative contribution of the different terminal types to the throughput growth.



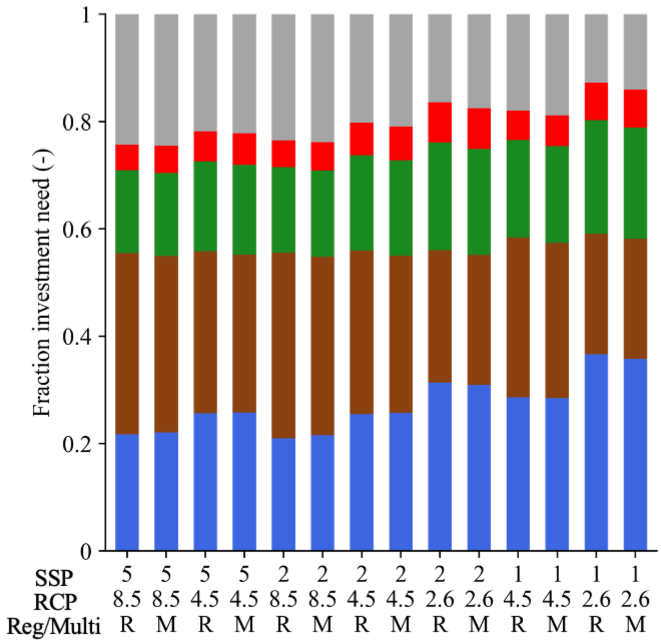
Supplementary Figure A4.3: Highest and lowest throughput scenario per port. Overview of the trade scenario that cause the lowest port throughput (a) and the highest port throughput (b).



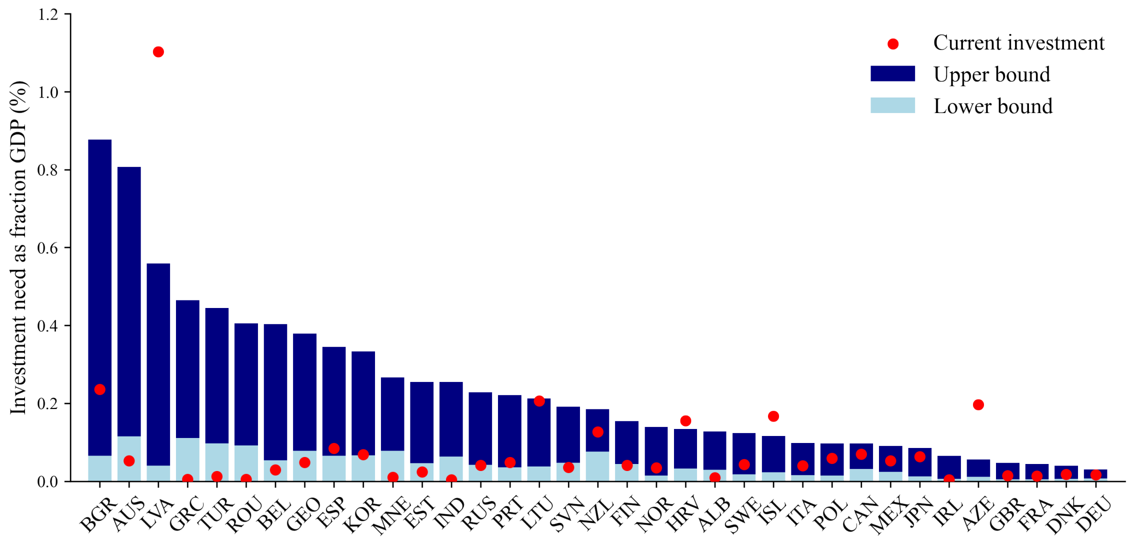
Supplementary Figure A4.4: Likelihood of negative and fast throughput change. The fraction of scenarios (out of 14) that indicate a negative throughput change per port (a) and a fast throughput growth, defined as a change of >300% (b).



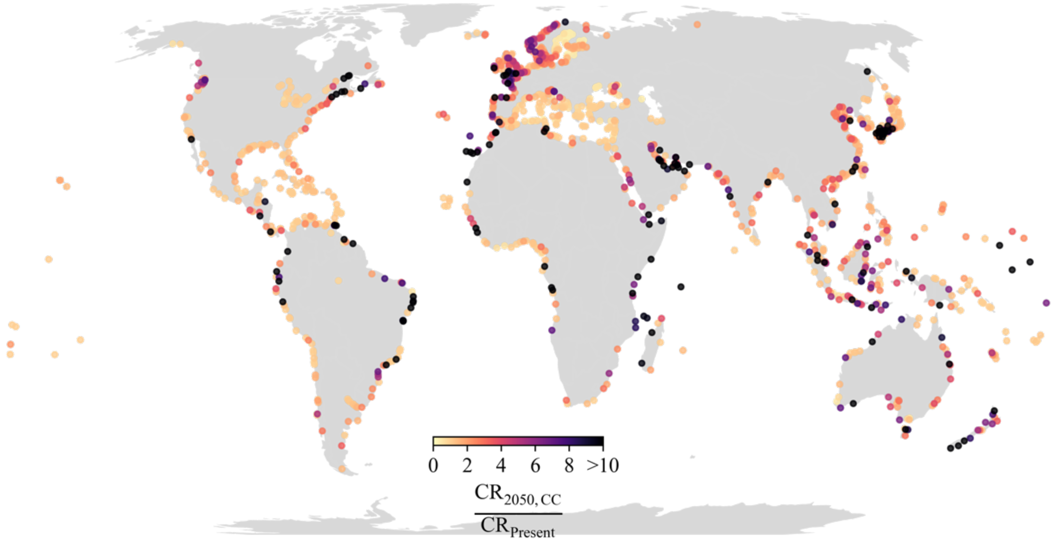
Supplementary Figure A4.5: Port area requirement for new port expansions. (a) The global area requirement for new port expansions to meet throughput demand for 2050, disaggregated by the terminal type. The uncertainty bar show the 10 to 90th percentile confidence interval based on the Monte Carlo analysis (Methods). (b) The relative contribution of the five terminal types to the area requirement.



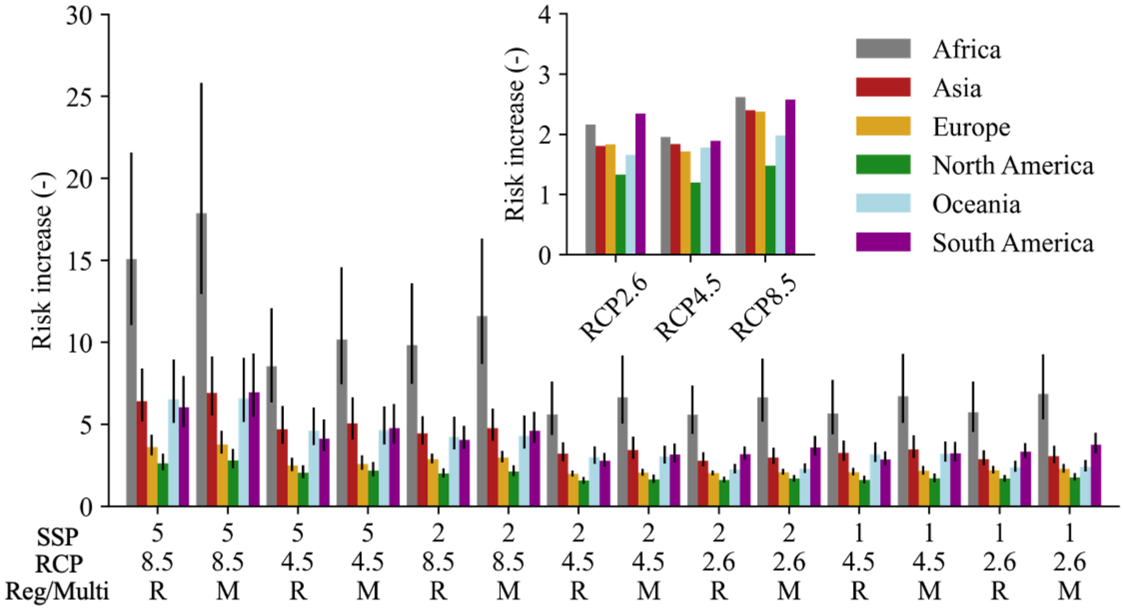
Supplementary Figure A4.6: The relative contribution of the five terminal types to the investment need.



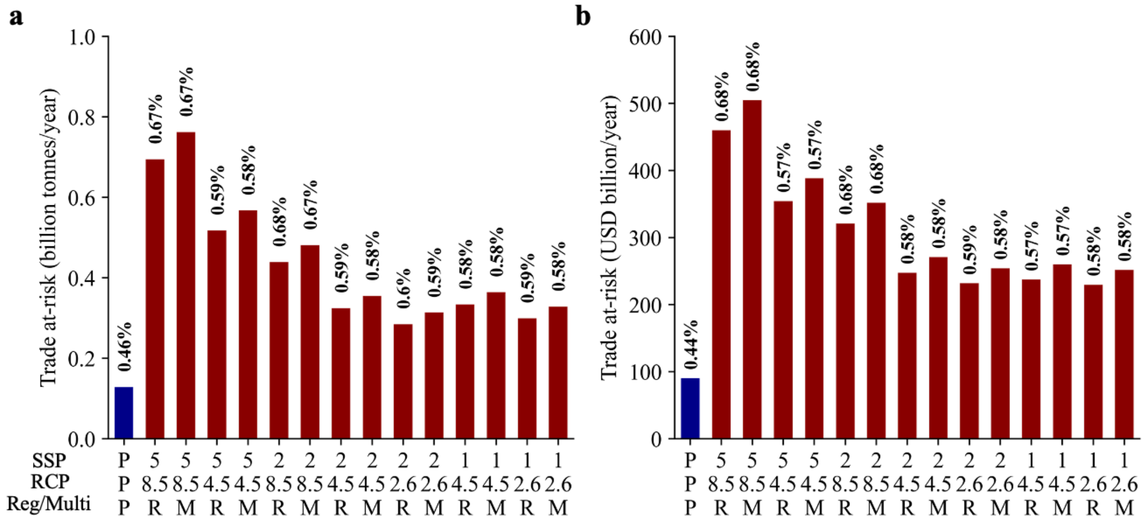
Supplementary Figure A4.7: Investment need as fraction of GDP in OECD countries. The light blue bar shows the lowest possible investment need as fraction of GDP, whereas the dark blue bar shows the highest possible investment need as fraction of GDP. The red marker indicates the current public expenditure on maritime infrastructure as included in the OECD infrastructure investment database (https://data.oecd.org/transport/infrastructure-investment.htm). The latter includes both spending on new construction and the improvement of the existing network.



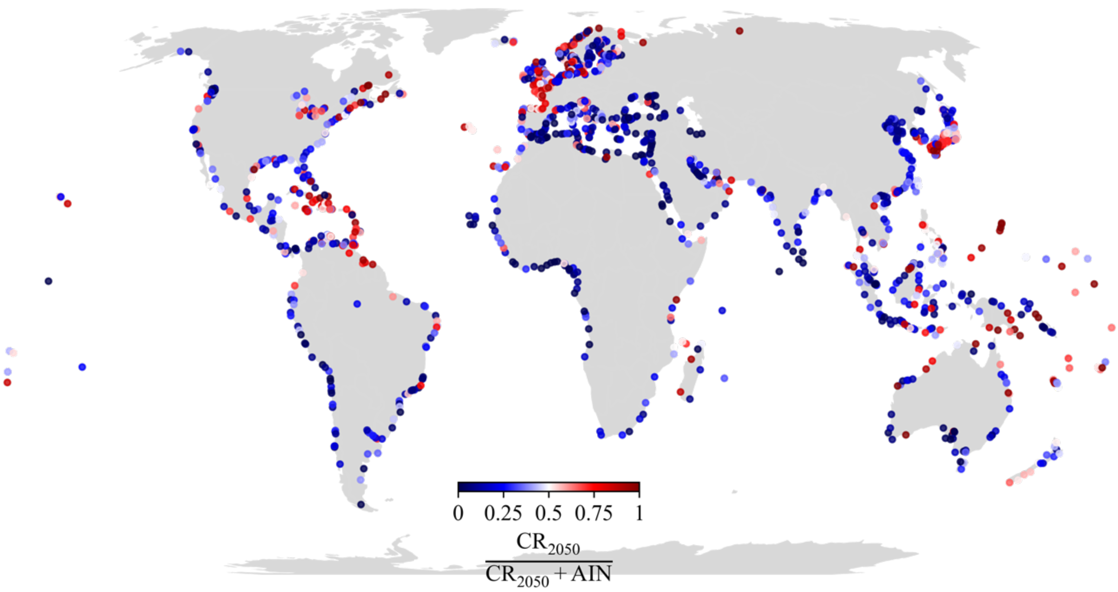
Supplementary Figure A4.8: Change in climate risk due to climate change alone. The climate risk in 2050 compared to the climate risk in 2015 because of a change in climate change alone (so no port expansions). The figure shows the mean across the scenarios.



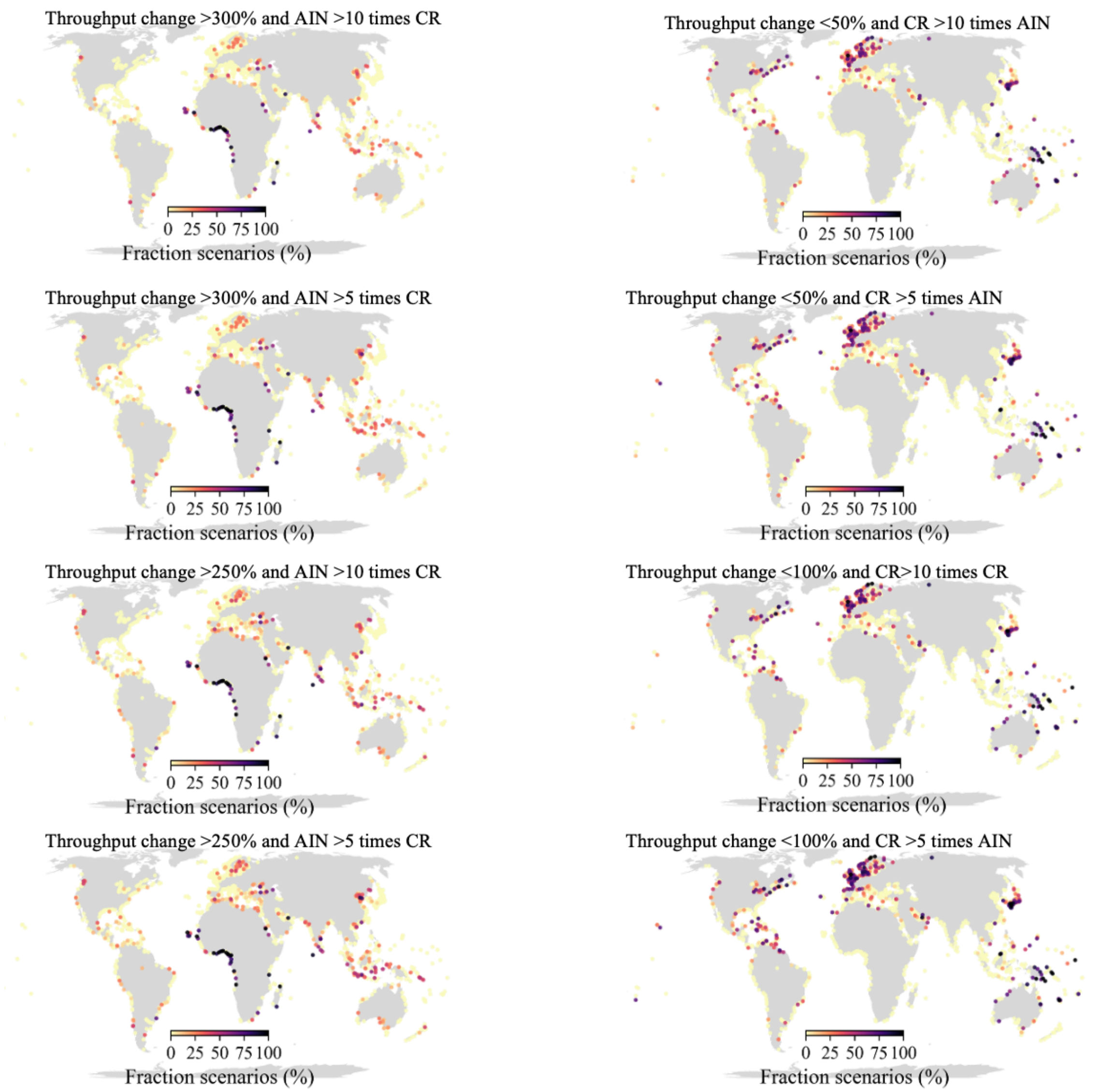
Supplementary Figure A4.9: Climate risk increase per continent. The risk increase ($CR_{2050}/CR_{present}$) per continent and scenario. The small plot shows the risk increase for the climate change scenarios only per continent.



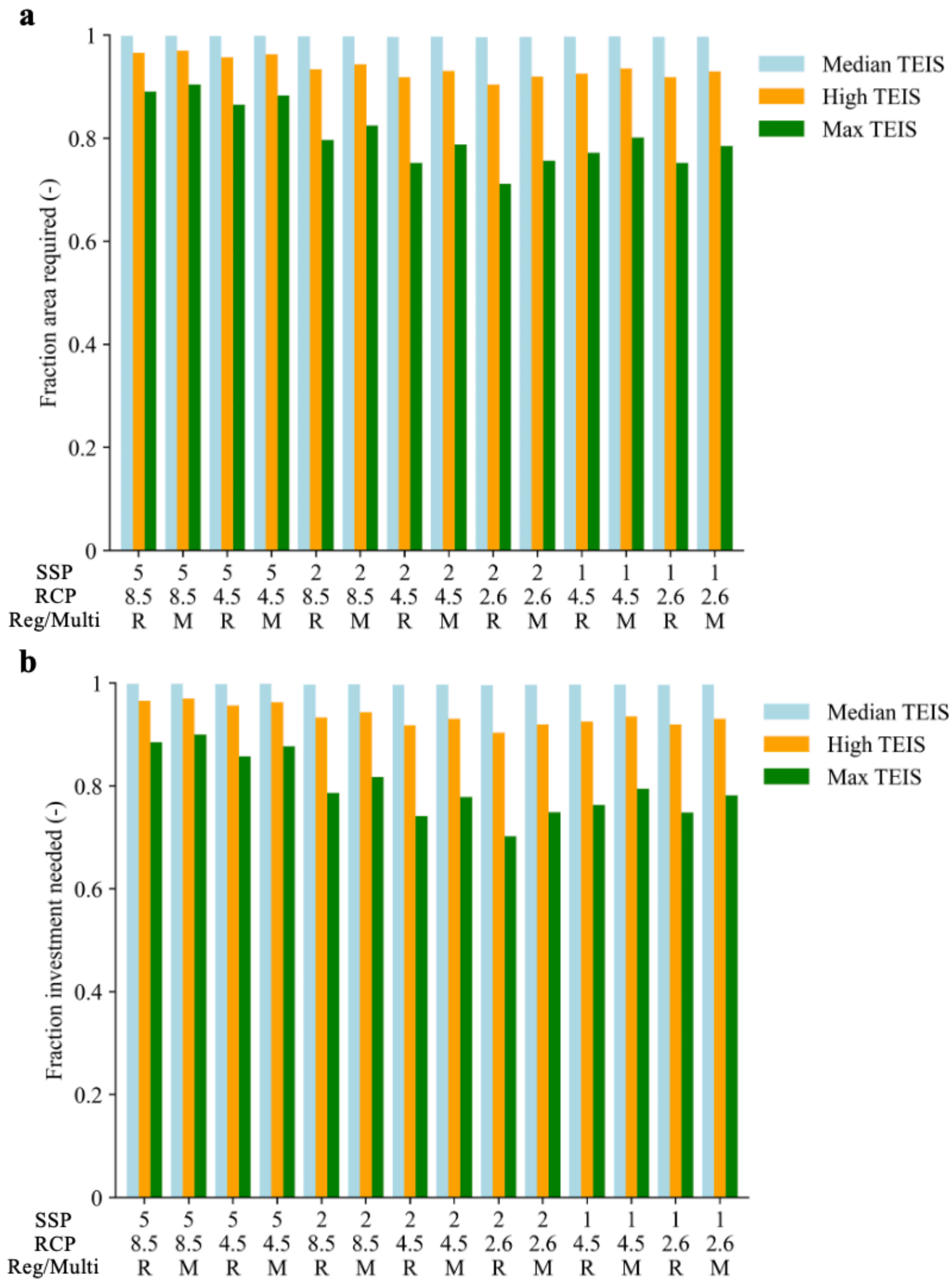
Supplementary Figure A4.10: The trade at risk due to port downtime. (a) The yearly average global trade at risk at present (P) and under the future scenarios expressed in billion tonnes per year. The numbers on top of the bars indicate the trade at risk as percentage of the global port throughput at present or in the future. (b) Same as (a) but expressed in terms of value (USD billion per year).



Supplementary Figure A4.11: Climate risk as fraction of budget to manage risks and plan new port expansions (CR + AIN). The fraction of future climate risk, expressed as in USD billion per year, compared to the annual hypothetical budget that port authorities need to set apart to manage climate risks and finance port expansions (annual investment need, or AIN, in USD billion per year).



Supplementary Figure A4.12: Sensitivity analysis of hotspots of expensive retrofitting and mainstreaming of adaptation. A comparison of different criteria used to evaluate the hotspots of adaptation mainstreaming (left) and expensive retrofitting (right). The top panel includes the criteria used in the main paper, whereas the bottom three panels show the result for different criteria by changing the throughput change threshold and the AIN to CR fraction.



Supplementary Figure A4.13: Influence of the terminal efficiency improvement strategies on the area and investment needs. (a) the fraction of the area required (1 indicating the baseline results in the main paper) for the median TEIS, high TEIS and Max TEIS scenarios (see Methods). (b) Same as (a) but in terms of the investment needs.

Supplementary Tables

Supplementary Table A4.1: Cost scaling factor across different regions globally

Regions	**Cost factor (-)**
Rest of Europe, North America, Australia, New Zealand	1
Southern Africa	1.1
Asia	0.5
Middle-East and Northern Africa	0.6
South America, Caribbean, Pacific, Eastern Europe	0.8

Supplementary Table A4.2: Parameters used in this study to derive the port area requirement. All parameters are modelled using a uniform distribution function between the lower and upper bound.

Parameter	Container	Dry bulk	Liquid bulk	General cargo	Source
t	4 - 8	12 - 18 for silo 25 - 45 for open	15 - 30	7 - 13	(Kox, 2016) (Kleinheerenbrink, 2012) (Ligteringen and Velsink, 2012) (Merk and Dang, 2012)
V_{TEU}	10 - 12	-	-	-	Expert judgement based on statistics from several ports
A_{TEU}	Supplementary Table A4.4	-	-	-	(Ligteringen and Velsink, 2012)
r	Supplementary Table A4.4	-	-	-	(Ligteringen and Velsink, 2012)
m	0.6 – 0.8	0.6 – 0.85	0.5 – 0.8	0.65 – 0.75	(Kox, 2016)
hs	-	5 – 10 for silo 10 – 20 for open	-	1.5 – 2.5	(Kox, 2016) (Kleinheerenbrink, 2012)
α	1.3 – 1.9	1.2 – 2.0	1.3 – 2	2.0 – 2.6	(Kox, 2016)
ρ_{cargo}	-	0.6 – 0.9 for silo 0.7 – 1.5 for open	0.5 – 0.9	0.4 – 0.8	(Kox, 2016) (Ligteringen and Velsink, 2012)
f_{area}	-	5 - 15	-	1.3 – 1.7	(Ligteringen and Velsink, 2012)
f_{bulk}	-	-	-	1.0 – 1.4	(Ligteringen and Velsink, 2012)
V_{area}	-	-	20 - 30	-	(Kox, 2016)

Supplementary Table A4.3**:** Parameters used in this study to derive the terminal construction costs. All parameters are modelled using a uniform distribution function between the lower and upper bound.

Parameter	**Container**	**Dry bulk**	**Liquid bulk**	**General cargo**	**RoRo**	**Source**
H_{ratio}	1.8 – 2.2	1.8 – 2.2	-	1.8 – 2.2	1.8 – 2.2	(Kox, 2016), expert judgment
C_{dredge}	10 - 25	10 - 25	-	10 - 25	10 - 25	(Becker, Hippe and Mclean, 2017)
F_{dredge}	0.5 - 1	0.5 - 1	-	0.5 - 1	0.5 - 1	Expert judgment
C_{yard}	105 - 155	-	-	-	-	(Becker, Hippe and Mclean, 2017)
C_{crane}	7 - 11	-	-	-	-	(Kox, 2016)
n_{crane}	80 – 120	-	-	-	-	Own analysis based on data in Wiese *et al.* (2009)
$C_{yard,eq}$	1 - 2	-	-	-	-	(Kox, 2016)
$n_{yard,eq}$	40 - 60	-	-	-	-	Own analysis based on data in Wiese *et al.* (2009)
R_a	-	-	-	0.001 – 0.005	0.001 – 0.005	(Hamburg Port Authority, 2017)
S_c			350 - 700			(Kox, 2016)
C_{pav}	-	150 - 250	-	150 - 250	150 - 250	(Hamburg Port Authority, 2017)

C_{silo}	-	-	15 - 25	-	-	Own analysis of several grain terminals (see Supplementary Note A4.2)
QLF	-	10,000 – 30,000 for import 25,000 – 75,000 for export	-	1.3 – 1.7	-	(van Vianen, 2015)
M_c	-	7000 - 9000	-	1.0 – 1.4	-	(van Vianen, 2015)
I_{eq}	-	14.5 - 26.5 for import 7.6 – 13 for export	-	-	-	(van Vianen, Ottjes and Lodewijks, 2011)

Supplementary Table A4.4: The gross storage density and ratio of average over maximum stacking height for different type of container yard equipment. Values taken from Ligteringen and Velsink (2012).

Equipment	**Ateu (m^2/TEU)**	**r (-)**
Straddle carrier	10 - 13	0.25 – 0.50
Reach handler	20 - 30	0.29 – 0.57
Rubber Tyred Gantry Cranes (RTG)	7.5 - 16	0.50 – 0.67
Rail Mounted Gantry Crane (RMG)	7.5 - 11	0.50 – 0.57

Supplementary Table A4.5: Comparison on area unit needs using the PPC model, the externally estimated ratios and existing rules of thumb.

Terminal type	**PPC model (tonnes per m^2)**	**Externally estimated ratios (tonnes per m^2)**	**Rules of thumb (tonnes per m^2)**
RoRo	-	4.1 (1.5 - 9.7)	2 (Hamburg Port Authority, 2017)
General Cargo	7.5 (4.7 – 11.6)	9.44 (3.3 – 15.6)	4 - 6 (Ligteringen and Velsink, 2012) 2.6 – 11.6 (Hamburg Port Authority, 2017)
Liquid	33.1 (20.8 – 53.7)	14.4 (2.1 – 23.2)	Oil terminals have around 40 – 50, while a LNG terminal has around 13 to 17 (Ligteringen and Velsink, 2012)
Dry bulk	19.4 (11.0 – 35.1) bulk in silos and 17.7 (9.8 – 34.3) bulk in open storage	14.2 (4.2 – 31.4) for bulk overall, 36.5 (12.9 – 56.9) for bulk in silos and 18.9 (10.6 – 33.9) for bulk in open storage	Dry bulk terminals for coal have around 7 – 38 for import terminals and 20 – 80 for export terminals (Kox, 2016)
Container	17.3 (11.0 – 27.0) for RTG, 19.8 (13.7 - 29.0) for RMG, 10.9 (6.9 – 17.1) for straddle carrier, and 5.9 (3.7 – 9.1) for reach handlers	21.0 (12.3 – 29.9)	0.7 – 5.7 TEU/m^2 (Drewry, 2010) 0.6 – 1.0 TEU/m^2 (Ligteringen and Velsink, 2012) 2.2 – 3.5 TEU/m^2 (Wiese *et al.*, 2009) *Note: a TEU is around 10 – 12 tonnes*

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