Failure modes in the maritime transportation system – a functional approach to throughput vulnerability

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ABSTRACT: Maritime transportation systems are essential for world trade; it is crucial to understand how these systems may fail, to be able to maintain their capacity. In this paper, the maritime transportation system is seen as a throughput mechanism; a technical system which serves its purpose by moving goods for its dependents. Understanding which key functions and capabilities are prerequisite for the ability to move goods, the loss of which are the failure modes, allows for the creation of a 'business continuity plan' for the maritime transportation system

Through two surveys and interviews with maritime transportation industry stakeholders, it was observed that while stakeholders in the industry have a solid focus on frequent operational risks, there is a lack of awareness of vulnerabilities, as well as methods for addressing and planning for low-frequency high-impact disruption scenarios. The presented approach provides a structured set of matrices of the key functions of the maritime transportation system, allowing stakeholders to increase the system's resilience through preparing to restore this limited number of critical functions.

KEY WORDS: Port resilience, failure modes, supply chain risk management, maritime transportation, business continuity planning.

1. Introduction

'*Plans are nothing; planning is everything*' – Dwight D. Eisenhower
'*No battle plan survives contact with the enemy*' – Helmuth von Moltke the Elder

The essence of the two statements above is that one may prepare for anything. However, no plan will be perfect; in the realm of supply chain risk management, disruptions will occur. One may argue that no amount of initial planning will prevent undesirable events from happening. Through preparing to restore the functionality of the transportation system, good planning will increase the understanding of the vulnerabilities of the transportation system and to help restore its ability to serve its dependents.

Maritime transportation is a prerequisite for global trade, as over 80% of global trade in goods are transported by ships [1]. In 2005, over 7 billion tons of cargo was moved by sea between 160 countries [2], constituting a great share of international volumes. The 2004 value of world import trade was $7.2 trillion dollars, where maritime transportation has been vital as an enabler. A key element in this picture is the seaports, acting as the connector between vessels, suppliers, users and land transportation. However, there is limited research available on the reliability of service for this vital node in global supply chains, and how it interacts with other elements of the maritime transportation system.

General trends in maritime transportation are consolidation and privatization; terminals are increasingly operated by large transnational terminal operators replacing local partners, and shipping companies increase their scope of control in the value chain [3]. Hyper-optimization of logistics chains was emphasized in the World Economic Forum Global Risks 2008 report [4] as one of four emerging global risks. An increased security focus in maritime transportation, introducing initiatives and regulations such as Authorized Economic Operator [AEO], Partners in Protection [PIP], Container Security Initiative [CSI], Customs-Trade Partnership Against Terrorism [C-TPAT] and 100 % container scanning are introducing new complexities for the flow of goods [5, 6]. The combination of industry consolidation and increased regulation results in tighter coupling and more complex interactions between the components of the maritime transportation systems, thereby increasing the vulnerability of the system [7].

Maritime supply chains are exposed to many disruption sources, leading to a number of system breakdowns every year. There seems to be a growing realization in research communities that the maritime transportation system cannot be seen as yet another set of nodes in the supply chain, but rather as integrated components, where failures do have severe consequences. De Martino and Morvillo [8] argue that ports until recently have not been seen as integrated components in the supply chain, although their focus is value creation. Carbone and De Martino argue earlier that existing research on ports in a business perspective is modest [9]. Robinson similarly suggests that ports should be included as elements in value-driven chain systems [10].

Learning from safety and reliability research, potential disruptive events may be categorized through the risk pyramid, see e.g. Bird and Germain [11]. In short, they presented that for each fatal accident, there were 10 serious accidents, 30 accidents and 600 incidents. This is a concept that may be transferable to supply chain risk management; for every severe disruption, one may assume that there are a number of moderate disruptions and a large number of minor incidents. In the following, evidence are shown suggesting that maritime supply chain stakeholders are aware of severe incidents, although they do not themselves prepare for such incidents.

A key question in supply chain risk management is whether to prevent an event from occurring, or to prepare to respond to a disruptive event. In this paper, the argument is that the current level of prevention measures is good for operational risks, as well as for the fairly obvious risks that would occur every few years. However, there are a number of events that can cause enormous harm to a supply chain, although they are not easily foreseen, and would occur infrequently. In the following, these are termed low-frequency high-impact scenarios [LFHI]. This paper proposes that a real-life prudent risk management strategy should include both incident prevention and preparation for post-incident response.

Prevention may take form in listing the common or likely risks, which are termed an enumeration approach. For instance, a warehouse manager will know that if he has experienced an electricity failure about once a month in the past, it is likely that this will continue to be a future risk to operations, unless certain conditions change. The focus of such an approach is the causes, where the system’s vulnerability can be reduced through removing the cause or strengthening the ability of the system to resist the risk.

The suggested method is not about identifying the causes of a disruptive event, but rather to understand the consequences such events have on the system. By looking at the maritime transportation system from a functional perspective – as a throughput mechanism, seeking what capabilities and functions are necessary for the transportation system to be able to perform its mission, one may protect these functions without focusing on particular hazards and threats. Through this, the functional failure mode [FM] approach identifies all possible outcomes and develops a plan to considerably reduce the number of surprises and reduce the time before the port and maritime transportation system is recovered.

This research is based on a set of working assumptions: Existing supply chain risk management methods are focused on causes of risk; to mitigate risks, these must first be foreseen. LFHI disruption risks stand out from operational disruptions; there is a need for organizations to recognize and understand these risks and to make a selection which to prepare for and mitigate, which is currently not done for maritime transportation systems. Also, the MTS differs from other transportation systems; traditional methods for addressing supply chain risks are not adequate, the distinctive features of the MTS mandates a designated method. Two research questions can be formulated for this paper:

RQ1: How may one identify potential low-frequency high-risk disruption scenarios in maritime transportation systems?
RQ2: How do one reduce systemic vulnerability towards low-frequency high-risk disruption scenarios in maritime transportation systems?

The remainder of this article will offer definitions, a brief literature review both for supply chain risk management and relevant port research, and an introduction to relevant concepts in section 2, insights from stakeholder interviews and surveys in section 3, the resulting failure modes in section 4. Section 5 offers a discussion, and conclusions are given in section 6.

2. Background

2.1 Definitions

Risk may be defined as *a triplet of scenario, frequency and consequence of events that may contribute negatively* [12]. Hazards and threats are *sources of potential damage*; Kaplan and Garrick describe risk as hazards divided by safeguards. In this, risks cannot be completely removed, only reduced. Numerous definitions exist for supply chains, see e.g. Mentzer et al. [13]. In this article, the following definition is used: *A supply chain or logistics system exists to move a product or service from suppliers to customers. The network can be seen both as a single system and a collection of interacting systems, involving people, technology, activities, information and resources.*

The key mission of the supply chain is to serve as a throughput mechanism of goods, and in hardship, protect the dependents from the consequences of disruptive events. Continued, in the context of maritime supply chain risk management, maintaining a supply chain mission focus, vulnerability is *the properties of a transportation system that may weaken or limit its ability to endure, handle and survive threats and disruptive events that originate both within and outside the system boundaries*, inspired by Asbjørnslett and Rausand [14].

Supply chain resilience has become a field of research the latest 10 years, numbers of definitions have been made, see e.g. Jüttner et al. [15]. Resilience is *the ability of the supply chain to handle a disruption without significant impact on the ability to serve the customer*. Resilience provides the ability to handling the consequences of a disruption, and does not address preventing a disruption from occurring. However, virtually all of the effort necessary to create a resilient system is exerted well before a disruption occurs.

Failure modes are defined here as *loss of the key functions and capabilities of the supply chain*, loss of any such would reduce or remove the ability of the system to perform its mission. The basis for the six failure modes used in this paper is the MIT Center for Transportation and Logistics Supply Chain Response project, for which several hundred disruption scenarios were assessed and grouped through grounded theory [16]. The concept of failure modes is well known and used within safety and reliability application [17, 18].

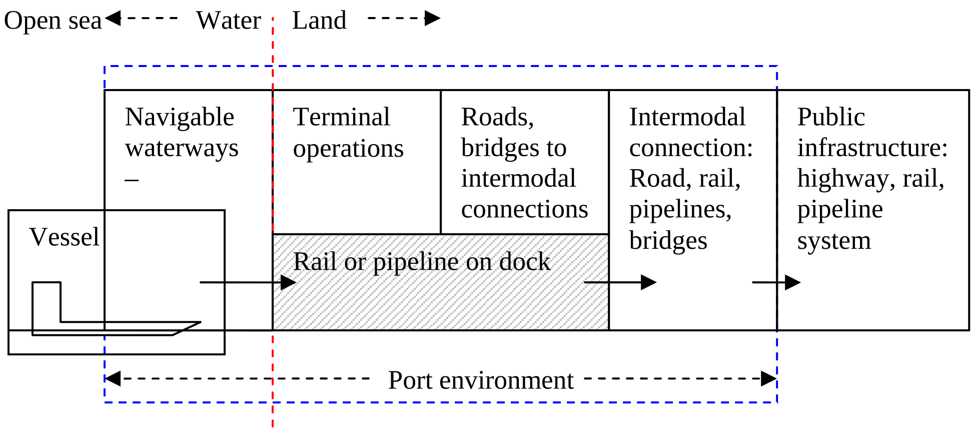
The U.S. Department of Transportation [19] defines the Maritime Transportation System [MTS] as composed of ports, intermodal connections, navigable waterways, vessels and users. The user is not considered explicitly, as the interest of the user is covered by the definition of the mission of the transportation system, but the four others are the elements used in this paper. A distinction between ports and terminals is made through ownership and their tasks.

Ports, as opposed to terminals, are to a large degree owned and operated by the public. Ports are considered to be *the business support functions around the terminals*, such as providing internal infrastructure like port road and rails, safety and security functions such as customs, investments, development and marketing. While some ports authorities operate the terminals themselves, a tendency is that terminal facilities are private facilities, where the port authority serves as a landlord. The terminal function, as defined here, refers to *the superstructure involved in the commercial operation of the port, i.e. the movement and processing of cargo*. Intermodal connections are *the links between the loading processes of goods in the terminal and the surface transportation system through road, rail, and pipelines*. Vessels are referring to *ships that carry goods over sea*. Barges are a special case that can be considered as vessels, although mainly operated on inland waterways.

System borders for the maritime transportation system, as defined in this paper, are *where the goods exit the port domain*. In this, navigable waters such as turning basins, canals and waters leading into open sea is included, open water transit is not. Similarly, on the land side, when goods exit the port infrastructure into the main logistics systems such as the public highway or main rail system (the hinterland transportation system), it is no longer within a port domain. In addition, vessels are key components in the maritime transportation system, and are therefore included.

The interaction between the elements of the maritime transportation system may be illustrated as in figure 1 below; this is a receiving end port. Sending the goods the other way would make this an export port, loading and unloading from vessels to vessels would be a transhipment port. The model thereby covers the maritime transportation system. System borders illustrate where the scope of the assessment ends. In short, goods are unloaded from the vessel to the terminal, before goods are loaded through the intermodal connections and are sent to the public infrastructure through the port infrastructure. The port environment encompasses the navigable waterways, terminal and intermodal connections. There are some variations affecting what constitutes terminal operation and what constitutes intermodal connections, illustrated by the gray area. Intermodal connections are dependent on port infrastructure, so elements of the port infrastructure are included in the scope of the intermodal connections.

Figure 1: Process of the maritime transportation system



2.2 *Previous research*

There is a substantial amount of literature on supply chain risk management, see reviews like Manuj and Mentzer [20], Juttner [21] and Vanany et al. [22]. Other relevant research include papers on supply chain disruptions [23-25], supply chain vulnerability [26-28], and supply chain flexibility and resilience [29, 30]. There are a number of noteworthy publications aiming at a practical approach towards supply chain risk management, see for instance the workbook on supply chain risk by Cranfield University [31], and Morrow et al. [32] on using the Supply Chain Council SCOR model on risk management.

Resilience is linked to what Zsidisin et al. [33] call Business Continuity Planning (BCP). They present a generalized framework to address supply chain vulnerability, and are the first that combine a cause-focused and a consequence-focused approach. Zsidisin also proposes a knowledge management system to allow the transportation system to learn from disruptive events.

History has shown that the losses, both to individual stakeholders, as well as to society, stemming from supply chain disruptions are large. Hendricks and Singhal [34] studied 827 publically announced supply chain disruptions in the period 1989-2000, and found that on average, stock returns of these companies were down nearly 40 %. The effects lasted, stock returns did not recover within few years. Equity risk for the companies also increased, on average 13.5 %. The effect on the company is that investors value them less after announcing supply chain failures. Stakeholders of the industry thereby have strong economic incentives in avoiding the consequences of supply chain disruptions.

Limited previous research was found on supply chain risk management with focus on ports and maritime transportation. Journal papers limit their focus to particular cases, such as more efficient optimization of box shipping [35], maritime security and security initiatives [36-38], port operation, competition and capacity [39, 40] optimal investment in port capacity [41], the role of port authorities in a changing port environment [42], the role of ports in value chains [8-10, 43]. Little attention is given to the overall maritime supply chain vulnerability picture. Research on maritime resilience include Barnes and Oloruntoba on security [5], and Fremont on organization of container trade systems [44].

2.3 Characteristics of the maritime transportation system

The maritime transportation system and maritime supply chains do differ from surface-based transportation in at least six aspects: 1) The size of conveyances, 2) the dimension of the maritime transportation system, 3) the dependence on key waterways due to geography, 4) legal issues, 5) the complexity of operations involving a large number of stakeholders, and 6) the share of international trade. To illustrate the dimensions, larger container ships may transport up to 15 000 TEUs [Twenty-foot Equivalent Units], which would require 7500 large trucks for land based operations. Maritime transportation systems have fewer nodes and modes to consider; even the United States only has 310 + ports, of which the majority in terms of numbers can only serve smaller ships or very specialized cargos. In the United States alone, the number of warehouses and truck terminals is assumed to be in the range of thousands, if not tens of thousands. In this manner, maritime transportation can be compared to rail systems, operating a limited set of ports and thereby a limited set of routes.

While ships can, in theory, travel anywhere on the oceans, major trade routes follows the shortest sailing paths. Key chokepoints of these are the Suez and Panama Canal, as well as straits such as the Malacca in Indonesia [45]. The dependence on the can be illustrated by the massive fluctuations in world shipping following the 1956-1957 and 1967-1975 closure of the Suez Canal [2, 46].

Legal issues include factors such as the Jones Act, banning foreign flagged vessels from operating on US domestic trades, and the 100 % container scanning initiative, introducing additional constraints into operation. The complexity of operations signifies the number of people and parties involved in operations. The key driver is the large volumes that need to be moved in a short time, requiring fast turnaround of vessels in port. In this manner, the maritime transportation can be compared to air transportation. In addition, a number of stakeholders in a ship un-/loading operation have no parallel in road transportation, e.g. Coast Guard, harbour control, pilots and tugs.

International trade constitutes a larger share of commerce in maritime transportation compared to land based systems. This introduces a set of complexities, such as customs and security needs, such as the contemporary piracy issue in the Bay of Aden.

2.4 Failure modes

Through the MIT Center for Transportation and Logistics Supply Chain Response project, several hundred disruption scenarios were assessed. Firms’ experiences with previous disruptions, as well as a thorough literature survey, gave insight to how disruptions affect supply chains. In total, about 150 supply chain stakeholders have been interviewed for the establishment of the failure mode concept. Using a grounded theory approach, the failures were broken down into types of failure. At the time of this assessment, five failure modes were identified, later revisions added one to six total.

The failure modes [47] can be summed up as the loss of capacity to supply, financial flows, transportation, communication, internal operations/capacity and human resources, which may be described as follows: Capacity to supply is the required ability to source provisions needed for the element to perform a given function; for a factory, this is inbound materials, utilities and electricity. Financial flows are the ability to access capital and liquidity / cash flow. Transportation is the ability to move materials, including those presently at work. Communication is understood in a wider sense, including enabling technology and data management. Internal operations entail the organization's processing capacity (e.g. converting materials into a good). Quality issues reducing outputs fall into internal operations. Loss of human resources singles out the human factor explicitly from internal operations – what are the personnel needs for the supply chain functions?

2.5 Vulnerability reducing strategies

Two ways of reducing vulnerability through increasing the resilience are important: Redundancy and flexibility. A practical implementation of a resilience strategy would have to include a combination of the two, based on a range of operational and market factors, such as criticality, practicability in implementation and not the least cost/efficiency trade-offs.

Redundancy is about maintaining the capacity to respond to disruptions in the supply network [16], which is the additional capacity that would be used to replace the capacity loss caused by a disruption. Redundancy is in essence about safety stock, inventory being its basic form [48], redundant production capacity, transportation capacity and IT systems are other forms. Over the last two decades, many companies have worked with 'lean' policies, cutting costs by reducing this sort of redundancies, resulting in tighter supply chains and higher quality of products and services. Sheffi therefore argues that redundancy at best may be regarded as a necessary evil, an insurance against risk; for vital resource, it may be necessary, although too much will come with an exorbitant cost.

Flexibility is about redeploying previously committed capacity [16]. Operational flexibility can increase resilience, allowing companies to respond quickly to disruptions. Examples of flexible capabilities include flexible contracts, allowing for quantity and delivery changes; flexible manufacturing facilities that may produce multiple products; a multi-skilled workforce; and strong customer and supplier relationships, ensuring continuity. Such capabilities do not come easily, as it requires fundamental changes in the organization and its supply chain relationships. General cargo ports that were normal before containerization became common in the 1950s onwards offered far greater flexibility than the current specialized container ports, being able to handle a wide variety of goods.

3. Case

Empirical insight into the problem was collected from interviews and visits to relevant ports in the US and Panama, and data from two MIT Center for Transportation and Logistics surveys were used. While the data material, except from the global risk survey, is only from US ports, insights may apply wider.

3.1 Interviews

16 semi-structured interviews were made with terminal operators, port authorities and the US Coast Guard in ports geographically distributed in California, Texas and New York and New Jersey, as well as in Panama. Operations of different sizes were included, terminals included both grounded and wheeled container shipping, break-bulk, reefer and Ro-Ro. Questions included contingency plans, perspectives on resilience, approaches towards risk assessment and management, and description on previous disruptions.

A catch-phrase that was expressed frequently was that 'if you have seen one port, you have seen one port'. In this, an interpretation is that the informants expressed their belief that a framework to understand the vulnerability of ports was not feasible, or at least do not exist at the moment. In general, the basic processes are to move goods on and off a boat to storage and then to another boat or hinterland. More particular, container shipping is by definition standardized. Thereby, a taxonomy of vulnerabilities in the MTS is feasible.

The US maritime transportation security act of 2002 [49] mandates that all ports should have a Maritime Transportation System Recovery Unit (MTSRU), where the US Coast Guard was given the responsibility to organize the efforts [50]. The goal of this is to prepare the port and stakeholders to respond, recover cargo flow, restore cargo flow to pre-incident capacity, and to resume commerce. Through this process, a cause-focused listing of all relevant risk is done. The stakeholders had oversight of the general process, had available information relating the outcome of the risk process and some had regular exercises. However, some respondents commented that such processes were not used for operational risk management; they were seen more as input for governmental grant applications.

The supply chain risk management processes of the larger terminals were enumerative, listing a wide variety of potential risk sources. However, the structure around the assessment was presented as not clearly defined with regards to who was responsible for the process, including updating it, intervals for updating and revising the models, inclusion of new elements et cetera. Minor terminal operators gave budgetary constraints as a reason for lack of resilience planning; predefined FMs may provide support and guidance for such processes.

3.2 Surveys

For the MIT CTL Port Resilience project, a survey was made with stakeholders in the port domain, including shippers, port authorities and terminal operators. A total 525 respondents provided insight into disruptions in the port environment [51]. The largest group of respondents was shippers (123), followed by carriers and terminal operators. A majority of respondents indicated that most delays were on average less than a day, and less than maximum two days. However, adding up types of failures, it seems that a disruptive event on average will occur every two weeks. On the longest delays, for most categories of failures, the majority of respondents replied that delays were no more than 2-3 days, except for labour-related disruptions.

An observation from the survey was that, although not conclusive, highly focused entities may not have a full view of the system. The respondents reported delays only for the elements that they were operating in, e.g. shippers provided information on intermodal connection delays, terminal operators on the terminal delays. This illustrates the need for models such as figure 1, showing the interactions between the stakeholders in the maritime transportation system.

The 2010 MIT CTL Global Risk Survey, involving 2400 supply chain respondents worldwide gave insight in thoughts on vulnerability mitigation and failure modes among supply chain stakeholders. Three pieces of information were particularly relevant for the FM approach: 54 % of 1350 valid respondents would spend more or much more on planning and implementing risk prevention measures, 30 percent would spend equal amounts on prevention and response. In this, a strong indication is given that prevention is considered more important than response among supply chain operators. The question did not specify whether already implemented measures should be considered.

Other explanatory factors covered by the survey include the industry of the respondent, his job function and his level of education [52]. Utilities, metal fabrication firms and manufacturers of transportation equipment favoured emergency preparedness, while primary metals industries favoured response preparedness. This may be explained through the application of just-in-time principles, where typically car manufacturing companies have more connected supply chains than mining companies. Transportation managers were more focused towards response, perhaps through having experiences that not all incidents can be prevented. Also, the higher the education of the respondent, the more he had preference towards response.

On being asked on the importance of failure modes on major supply chain disruptions, 1317 valid responses were given, where the by the respondents perceived 1st, 2nd and 3rd most important failure modes were weighted as 3, 2 and 1. The key insight is that loss of supply was the primary worry of supply chain stakeholders, followed by interruption of internal operations. Loss of communication was rated as the third most important mode. Labour availability was rated as the least important. At the time of the survey design, demand was considered a failure mode; in later revisions, estimating demand is considered a factor in the supply chain design, not a key capability or function of the system itself. Demand is therefore excluded as a failure mode. However, it is somewhat related to demand failure in the sense that it affects revenues. Therefore, financial flows (access to liquidity) are possibly more important than what the numbers indicate.

Table 1 – failure mode importance (1317 valid responses) - (a) Explanation of metric: Respondent's 1st, 2nd, and 3rd choices of most important risk were weighted as 3, 2, 1. the metric shown is the weighted average response. The metric approximates the probability that a risk wild be selected as one of the most important risks by a respondent.

Failure mode (Type of supply chain disruption)	Weighted average importance (a) - worldwide
You lose supply of quality materials (e.g. supplier fails or cannot deliver, bad product quality, etc.)	25.9%
Your own internal operations are interrupted (e.g. power failure, machine breakdown, fire, etc.)	22.9%
Sudden drop in customer demand (e.g. new competitor, financial crash, etc.)	16.0%
You cannot communicate with vendors, customers or other sites (e.g. systems fail, internet down, etc.)	12.1%
You cannot ship or deliver your product e.g. no transportation, ports closed, roads blocked, etc.)	11.4%
You run out of cash (e.g. credit tightens, customer payments late, etc.)	6.0%
Your people are not available (e.g. mass illness, work stoppage, etc.)	5.7%

1441 valid responses were given to the frequency of failures related to the different failure modes. Observing the frequency of failures, similar results as in table 1 are found: Disruptions related to supply of materials and internal operations are the most frequent, financial problems and labour shortages are the least frequent. A flaw of this question was that the question asked for ‘what types of disruptions are the most important for your company *at your site* [highlight is by authors] to be prepared for?’ In this, the respondents may have been lead towards answering about operational issues, which are supply and internal operations. The answers are however consistent with the answers presented in table one.

Table 2 – failure mode frequency (1441 valid responses)

Global results - frequencies of major disruptions	Never	Rarely	About Yearly	Weekly or monthly	Almost daily	N/A
Your own internal operations are interrupted (e.g. power failure, machine breakdown, fire, etc.)	13.9%	51.0%	21.5%	10.8%	1.5%	1.2%
You cannot communicate with vendors, customers or other sites (e.g. systems fail, internet down, etc.)	19.4%	55.3%	17.7%	6.1%	0.6%	0.9%
You lose supply of quality materials (e.g. supplier fails or cannot deliver, bad product quality, etc.)	7.2%	38.0%	31.4%	19.4%	1.5%	2.4%
You cannot ship or deliver your product (e.g. no transportation, ports closed, roads blocked, etc.)	17.7%	51.0%	21.7%	6.3%	0.6%	2.6%
Your people are not available (e.g. mass illness, work stoppage, etc.)	42.0%	44.6%	9.0%	2.6%	0.6%	1.2%
You run out of cash (e.g. credit tightens, customer payments late, etc.)	57.5%	29.1%	6.5%	3.8%	0.6%	2.5%
Sudden drop in customer demand (e.g. new competitor, financial crash, etc.)	18.4%	48.4%	24.3%	5.8%	0.9%	2.2%

3.3 Insights from the empirical study

Key insights from the empirical study could be summarized as:
I1: Respondents have an operational focus; in this, they spend their efforts on frequent minor disruptions rather than the large issues.
I2: Supply chain stakeholders in general are focused on prevention rather than preparing to respond; given the current investments, perhaps new investment should be directed towards response?
I3: Stakeholders do know that larger events do happen, and they know they can be very costly, yet they do not prepare for LFHI scenarios.
I4: Port stakeholders find their port unique. In this, although the physical infrastructure is different between ports, procedures and process offer potential for learning from others. This point seems undervalued by the stakeholders.
I5: There seems to be little visibility throughout the maritime transportation system.

Stakeholders focus on their own operations, and seek to mitigate the risks they see at hand. Several stakeholders complained about lack of resources for more in-depth risk planning. Following the stakeholders operational focus, an enumeration strategy for determining risks is a rational choice; frequent historical failures, as well as risks that would be on top of the mind for assessors, are likely to be relevant for daily operation.

Stakeholders know that larger events do happen. Given the nature of these events, as expected, all interviewees gave examples of major disruptions, only a few could give insight into disruptions where their own organization was involved. Examples of the latter were stakeholders from the ports of Los Angeles / Long Beach, who gave examples from the 2002 dockworker strike. The fact that, from the interviewees' perspective, major disruptions either happened to someone else or a long time ago reduces their incentive to include major disruptions in their vulnerability management planning. Stakeholders in the maritime industry know that supply chain disruptions are costly; they know that costly glitches have occurred in the past, in spite of this; the study showed that stakeholders do not include catastrophic failures in their risk management systems.

The MIT CTL Global Risk Survey indicated that supply chain stakeholders in general are focused on prevention and frequencies rather than preparing to respond after incidents have occurred. As presented in tables one and two, the importance of failure modes and frequency of occurrence coincide.

None of the respondents used a consequence-focused approach in their supply chain processes. The proposed failure mode approach, which is presented in the next section, would contribute to the risk management process through focusing on low-frequency high-impact scenarios.

4 Failure modes

4.1 Developing a failure mode framework for the maritime transportation system.

Combining the identified failure modes with the elements of the maritime transportation system gives us the failure modes of the maritime transportation system, as may be seen in table 3. Each of the failure modes represents the loss of the ability to perform a critical function in the maritime transportation system.

Table 3: Failure modes in maritime transportation

Element / Failure mode	Port services –loss of:	Terminal – loss of:	Intermodal Connection – loss of:	Navigable Waterways – loss of:	Vessels – loss of:
Supply	Port supplies, utilities and infrastructure, tugs, safety boats	Terminal supplies, utilities and super-structure	Infrastructure leading to public infrastructure system, supplies for transportation and maintenance	Navigable water	Availability of vessels in market - type, size, features, characteristics
Financial flows	Access to capital, liquidity and revenue to fund operations and expansion of infrastructure	Access to capital, liquidity and revenue to fund operations and investments in superstructure	Revenues, access to capital and liquidity to invest in warehouses, storage yards and connecting infrastructure	Access to capital and, investment for dredging, safety measures and expansion	Revenues, access to capital and liquidity, for operating and investing in vessels
Transportation	The ability to move equipment and people within and through the port	The ability to move goods and people within the terminal	Equipment for moving and transloading goods to surface transportation: e.g. trucks and trains	The ability to move goods and people within and through the navigable waterways	The ability to move vessels
Communication	Communication, coordination and information systems across port players and between ports	Communication, coordination and information systems within terminal and to port	Oversight and the ability to document and coordinate cargo shipment, communication between parties – stevedores, truckers, terminal operators	N/A – Redundant with port communication	Coordination and control with other vessels and land
Internal operations / Capacity	The ability to move and position vessels, maintain safety and security, invest, develop and market port.	Loading / unloading, processing, documentation, Capacity	The ability to transload goods between surface transportation and vessels, including processing and storage.	Air and sea draft, width of channels	Loss of ability to operate vessels, including, including failure of loading gear and pumps
Human resources	Personnel operating port functions, supporting business	Personnel operating terminal	Personnel responsible for managing and performing transloading operations	Support services personnel for clearing waterways, dredging, maintenance.	Skilled vessel crew for operation

4.2 Port failure modes

Supply for ports is about which supplies are needed for operating in a wide sense. In a daily operation, utilities and infrastructure are the vital needs, such as electricity, wastewater systems and fresh water. Transportation infrastructure needed for port operation include roads, rail, bridges, pipes, and piers. For the port to serve as business support for the trade, supplies from external service providers are needed, such as the availability of tugs for moving and positioning vessels, Coast Guard vessels for security functions et cetera. July 23rd 2006, heavy rains overwhelmed the Citgo refinery treatment system at the Calcasieu Ship Channel, Louisiana, USA, leading to 40 000 barrels of oil being spilled. The US Coast Guard thereby closed the channel for cleanup for six days (Informant / Oil Daily). The failure of utilities influenced the operation of the port system, as the environment was given priority to business operation.

Financial flows in ports are about securing access to revenues, liquidity and capital to fund operations and expansions of infrastructure investments are typically subject to substantial subsidies from local authorities, wishing to draw more industries to the region, although for the US case, it does not always coincide with infrastructure and industry investments (Informant). Policy makers are thereby vital for many port development projects.

Transportation in the port is the ability to move people and equipment within and through the port, needing vessels, cars, fire engines et cetera. Flexible work vessels may perform a wide set of operation, from deploying oil spill protection measures to serving as supplementary fire fighting equipment.

Communication within ports include the infrastructure needed to upkeep these functions, involving elements such as phone lines, mobile phone masts, data networks, internet access, as well as information management systems. Throughout interviews with port and terminal stakeholders as a part of this research project, losing the ability to communicate was a major concern, both between port stakeholders and within terminals; in case of phone system failure, several of the stakeholders suggested encrypted radio systems coupled with training and usage protocols as a good solution to increase the robustness of this function. An informant had their local cell phone provider set up a list of phone numbers to be given preferential treatment in case of network overload in the port zone. Such a low cost simple measure increases the likelihood that vital communication may continue uninterrupted.

Internal operations and capacity in ports is about the ability to move and position vessels, maintaining safety and security, as well as to develop, invest and market the port. The wide range of tasks, from purely operational to long term strategic investment makes this a complex task. For instance, the port authority of Long Beach, LA, has established mobile command post units. These may be made available for several units in crisis situations, such as police, customs and fire fighting. For a limited investment, they have secured a backup to their facilities, in addition to having a flexible asset for on site disaster management.

Human resources in port operation involve the personnel that perform the port support services, such as administration, security personnel, and governmental agencies like customs. It is important to realize that a lot of the port functions are performed by external personnel, which the port has less control over, as they are not employed by the port.

Table 4: Elaboration of failure modes for ports

Port	Failure mode: Loss of	Elements that may be backed up	Example	Advantage	Disadvantage
Supply	Port supplies, utilities and infrastructure	Electricity, wastewater, water, roads, rail, land area, inventory, tugs, pilot boats	Contract with tug company for an increased capacity of tug services in case one should fail	Robust capacity increase, safety function	Cost
Financial flows	Access to capital, liquidity and revenue to fund operations and expansion of infrastructure	Financing, government support, liquidity, revenues	High level of liquid assets and loan bearing capacity for investment available	Allows for operations in a liquidity squeeze and expansions without external support	Alternative cost of underutilized liquid assets
Transportation	The ability to move goods and people within and through the port	Transportation providers, trucks, lifts, stackers, gantry cranes, chassis	Ordering flexible multi-purpose work vessels for port	Access to vessels that may solve a wide spectre of tasks	Cost for investment, training and operation
Communication	Communication, coordination and information systems across port players	Phone lines, mobile phone, data systems and networks, internet access	Secondary data storage / server system that mirrors original	Record keeping, availability in case the primary system is lost	Costs for equipment and training
Internal operations / Capacity	The ability to move and position vessels, maintain safety and security, invest, develop and market port.	Berth spaces and lengths, support vehicles and vessels, business strategies	Acquiring secondary mobile command posts	Access to secondary command locations, may set up local command posts in case of emergencies	Cost, need for training
Human resources	Personnel operating port functions, supporting business	Port authority, pilots, managers, security, technicians	Cross-train workers	Allows for workers to do more tasks, more flexibility	Cost, union issues

4.3Terminal failure modes

Supply for terminals is about which supplies are needed as for ports. In a daily operation, utilities such as electricity, wastewater systems, fresh water are important, on top of the services provided by the port. For instance for electricity: a number of operations in a terminal cannot be executed without access to electricity, what sort of back-up generators exist, and for which functions? One terminal on the US west coast reported power outages on average twice a week, often lasting over 1 hour, effectively hindering them from operating cranes to load and unload ships.

Financial flows in terminal operation are about having access to capital, liquidity and revenues to fund operation and investment in terminals. Terminals are privately operated entities that have a wide choice of activities to raise liquidity. Examples include extending their line of credits and pre-approved loans using assets as collateral to selling assets, issuing equity and selling the business itself.

Transportation in the terminal is about moving goods from the quay and vessel side to storage facilities, the intermodal side or other vessels. The type of transportation needed depends on the cargo type, but general equipment would be trucks, yard-donkeys, lifts, stackers, gantry cranes and chassis for containerized goods, conveyor belts for dry bulks and pipes for liquid bulks. Limited space in certain ports demands diligence when considering alternative mode if a system element fails, hampering inter-terminal transportation.

Communication within terminals include the infrastructure needed to upkeep these functions, involving elements such as phone lines, mobile phone masts, data networks, internet access, as well as information management systems. Company-internal data systems for ensuring the integrity of goods and keeping track of their whereabouts are vital, in particular for container trade. Technology-intensive container ports rely on complex data systems for keeping track of the whereabouts of boxes, and to assign drivers the right container. Such systems may fail with immediate consequences for terminal throughput.

Internal operations and capacity in terminals relate to the superstructure needed for terminal operation, such as storage space, cranes, conveyors, pipes, as well as inventory policy. What type of equipment is needed depends on cargo type, while liquid bulk needs piping and tanks; box shipping depends on cranes, stackers and flat land for stacking boxes. Inventory policy is an issue in determining systemic resilience: The larger the inventory, the longer the system can protect end users from consequences of disruption.

Human resources in terminal operation are vital factors. In particular in the US, dock workers have strong unions and have show willingness to use this, see the 2002 strike and following lockout of the 27 ports on the US east coast [48] (referred to earlier). Besides dock-workers, managers and technicians are important, the latter to maintain and repair the equipment on which the terminal operations rely. Factors such as degree of union control and having good relationships with workers can highly affect the probability of a labour-related shutdown, as well as the consequences of any such. The scope of possible restorative actions is also related to the degree of unionization.

Table 5: Elaboration of failure modes for terminals

Terminal	Failure mode: Loss of	Elements that may be backed up	Example	Advantage	Disadvantage
Supply	Terminal supplies, utilities and superstructure	Electricity, wastewater, water, land area, inventory, spare parts	Install generator capacity for operating IT and communication systems plus limited service of cranes / superstructure	Ability to use systems and move some goods in case of electricity outages	High cost for unused capacity, space and maintenance need
Financial flows	Access to capital, liquidity and revenue to fund operations and investments in superstructure	Financing, ownership, revenues, margins	Keeping higher share of liquid assets / cash / credit	Access to capital for operation in a squeeze	Alternative cost of underutilized liquid assets
Transportation	The ability to move goods and people within the terminal	Transportation providers, trucks, vans, lifts, stackers, gantry cranes, chassis,	Increase number of heavy-lift container stackers (which can lift both empty and full containers)	Equipment may perform more tasks, increasing flexibility	Increased capital and operational expenses
Communication	Communication, coordination and information systems within terminal and to port	Phone lines, mobile phone, data systems and networks, internet access	Secondary encrypted radio system, with training and communication rules	Efficient communication and coordination in time of crises	Some extra costs for equipment and training
Internal operations / Capacity	Loading / unloading, processing, documentation, Capacity	Storage space, cranes, conveyors, stackers, inventory	Adjusting inventory policy according to criticality of goods	Buffer stocks in case of disruptions	Cost, competitive disadvantage
Human resources	Personnel operating terminal	Longshoremen, stevedores, drivers, managers, security, technicians	Back-up knowledge	Easier to train new / replacement personnel, overview of knowledge needed	Costs, may create fear of replacement by labourers & unions

4.3 Navigable waterways failure modes

In the categorization of functions the waterways are considered first; how can one understand the category supply of navigable waterways? For instance, say a canal leading into a port was blocked due to a foundered ship? To understand the graveness of this: are there other canals leading into the port? Is there any heavy-lift capacity in the region available to clear the ship from the canal? To give an example (informant), there is no regular heavy lift capacity on the US West Coast, illustrating a lack of the most obvious restorative capacity. Blockage may stem from other causes; in case of an oil spill inside a harbour, the coast guard may close the port until the spill is cleaned up, to prevent spreading. High priority of environmental welfare may lead to substantial losses.

One example of a disruption in the supply of maritime waterways is the January 24th 2010 oil spill in Port Arthur, Texas. A tug pushing two barges collided with the 807 foot tanker Eagle Otome, spilling about 11 000 barrels of oil. The Sabine Neches Waterway was closed to accommodate clean-up, leading to an estimated loss of USD 200 m per day of closure [53]. On an average day, 150 barges and 15 tankers pass through the closed channel [54]. The waterway remained fully closed for 5 days, and had limitations for traffic for another two weeks.

Transportation in navigable waterways may include factors related to navigational support, such as the availability of tugs and pilot boats. Larger vessels need tug support to manoeuver in ports, in particular through narrow waters and in bad weather. Lack of such capacities will introduce constraints on operation and throughput.

Financial flows regarding navigable waterways belong to a broad category. Dredging and investment in waterways is most often financed by the public, quite often as a part of a regional development strategy. In the US, the work was until 1977 uniquely done by the US Army Corps of Engineers, now it is mostly done by private contractors [55]. A key question is therefore: who decides which ports and channel should get invested in, and what sort of a political process is this?

Capacity constraints to waterways may change: In many cases, dredging is required to maintain access for larger ships- lack of such, or external events such as landslides may change and limit the access and passage to smaller vessels. Given a year of little rain, water levels in rivers will be lower than usual, similarly reducing the accessibility of larger vessels. Capacity constraints may also arise from other sources, such as policy. For instance, the Bosporus strait imposes strict condition on passage of dangerous cargo such as oil – they may only pass in daylight and require high pilotage fees.

Communication can include such things as traffic control in busy waters. The loss of such a function would reduce capacity, as traffic control allows for moving a higher number of vessels through busy waters without compromising on safety. To be operated safely, a traffic control system again needs skilled operators, radars etc. to keep oversight over ship movements, communication gear for direction to vessels and so on.

The Human Relations function indicates that people take parts in making waterways available, as indicated in the categories above. Labour actions and conflicts should therefore tick warning lists when they occur: A pilot strike would for example effectively block the port, as vessels could not call the port without this competence – some ship owners for this reason choose to provide training for their crews to attain pilotage certifications.

Table 6: Elaboration of failure modes for navigable waterways

Waterways	Failure mode: loss of	Elements that may be backed up	Example	Advantage	Disadvantage
Supply	Navigable water	Waterway markers, dredging equipment, salvage gear, heavy lift capacity, oil spill protection equipment	Surveying sea-bed, available dredging / sea-bed clearing equipment	Port may clear channels / waterways themselves, before proper equipment arrives	Cost, need storage and training
Financial flows	Access to capital and, investment for dredging, safety measures and expansion	Investment in dredging, safety, expansion	Investment policies for dredging and channel clearing	Government can increase funding for dredging (US: army corps of engineers)	Cost, political issues
Transportation	Navigational support vessels, such as dredging barges, maintenance vessels for waterways.	Dredging barges, work vessels for etc. oil spill cleaning (ex: oil spill in Texas).	Mandate tug assistance through certain narrow waters	Lower risk for collisions, groundings	Cost, capacity issues
Communication	Not Applicable / overlaps with port communication				
Internal operations / Capacity	Air and sea draft, width of channels	Bridge and sea clearance	Expanding channels	Allows larger vessels to enter, increase flexibility of system	Cost
Human resources	Support services personnel for clearing waterways, dredging, maintenance.	traffic control, personnel for waterway maintenance, clearing and security	Contracts and training with key personnel	Faster response when disruptions hit	Cost, competitive issues

4.4 Intermodal connections failure modes

Supply for intermodal connections include such factors as availability of roads, rails, loading gear, fuel and parts. An example in loss of this function includes loss of vital road or rail connections to the extended transportation network. For instance: the port of Miami, USA, is located on an island connected to the main land with one bridge – the Port Boulevard Bridge. In case the bridge is blocked or destroyed, the port is no longer connected to the larger road and rail network, severely impacting its operation.

Financial flows include access to capital, liquidity, investments and revenues. The function can be performed within the terminal or at a separate site, and may be owned by the terminal operator or separate entities. In this, access to capital may be gained through both increasing credit lines and selling assets. Third party providers may be relevant for performing the transportation work, reducing the investment needed.

The transportation part of the intermodal connections involves the trucks and trains that do the movement of goods from terminals to the extended supply chains. In addition to owned companies, third party logistics providers and the availability of a spot marked should be kept into consideration. As defined previously, the transportation work in question for this method is to move goods out on a rail or motorway network, the haulage beyond this is not defined as within the maritime transportation system.

Communication in intermodal connections would include coordination, reporting, documenting integrity of service, routing and scheduling of goods and cargo, et cetera. In transportation security schemes such as C-TPAT, the ability to document the whereabouts and integrity of a container, in effect that it has not been tampered with, is essential for rapid flow of goods. If one should lose this function, guaranteed rapid treatment through customs etc. could not be ensured, inflicting delays on the flow of goods.

Internal operations and capacity in intermodal connections covers factors such as inventory, storage space and transloading space. For instance, in land-usage intensive cargos such as car freight, the availability of hinterland storage is vital, or else the port will be clogged with cargo in case of demand variation. An example of this is the situation of the port of Los Angeles following the 2008 financial crisis, where car shippers had to rent a substantial amount of extra acreage to park unsold cars [56].

The human element in intermodal connections is vital; land-based transportation is labour intensive, and without it, supply chains immediately break down. One example is the 1997 UPS-Teamsters strike, causing a 15 day full breakdown of the UPS transportation system, see e.g. Rothstein [57]. Relationships with labourers and unions are certainly a factor in prevention, as with ports, where they dictate the scope of possible restorative actions.

Table 7: Elaboration of failure modes for intermodal connections

Intermodal connections	Failure mode: loss of	Elements that may be backed up	Example	Advantage	Disadvantage
Supply	Infrastructure leading to public infrastructure system, supplies for transportation and maintenance	Roads, rails, bridges channels, fuel, parts, chassis	Plan and use multiple modes though investing in on-dock rail connections	Connects the port to a separate infrastructure piece, increasing robustness in infrastructure	Cost, area usage,
Financial flows	Revenues, access to capital and liquidity to invest in warehouses, storage yards and connecting infrastructure	Investment, access to capital, liquidity, ownership, revenue	Keeping higher share of liquid assets / cash / credit	Access to capital for operation in a squeeze	Alternative cost of underutilized liquid assets
Transportation	Equipment for moving and transloading goods for surface transportation	Trucks, lifts	Use multiple providers of services, including spot market	Pre-disruption relationship ensures support in crisis	Cost, need to commit volume to all suppliers
Communication	Oversight and the ability to document and coordinate cargo shipment, communication between parties – stevedores, truckers, terminal operators	Routing systems, communication with providers, IT systems,	Set up parallel IT systems	Robustness in communication, oversight, availability of data	Cost for setup and maintenance
Internal operations / Capacity	The ability to transload goods between surface transportation and vessels, including processing and storage.	Inventory, spare chassis, storage and transloading space	Contracts for backup storage facilities	Buffers for cargo flow in case of disruption, to not clog port area,	Cost, separate locations, may introduce inefficiency through creating excess storage
Human resources	Personnel responsible for managing and performing transloading operations	Drivers, management, planners	Organizing skill-specific backup plans, e.g. rail operators	Available personnel to perform critical tasks	Cost

4.5Vessels failure modes

Supply in the vessel category includes factors such as the market availability of particular classes of vessels, with factors such as cargo carrying type, size, equipment and certifications. Following the second oil price shock, in 1980, demand spikes for coal led to severe congestions in the major coal-loading ports [58]. The central US coal export port was Hampton Roads in Virginia, USA, providing 48.6 million tons, 72% of total US coal export in 1980. The combination of Japanese steel mills converting en masse from using oil to coal (informant) and decreasing outputs from Poland (24.5 million tons in 1979 to 10 million tons in 1981), led to one of the world's worst port congestions ever. In the first few months of 1981, an average of 150 panamax [60-80 000 dead weight tons [dwt]] bulk vessels were waiting about two months to load. To illustrate the scale of the event, 153 ore and bulk carriers were delivered from yards this year [59]. Assuming that the waiting vessels were 60 000 tons each, a small panamax class vessel, 9 000 000 dwt of the world total bulk fleet of 29 416 000 dwt [59], over 30 % of the world bulk fleet, was waiting off Hampton Roads, significantly drawing capacity from the world market.

Financial flows on the vessel side include revenues and margins for vessel operation, as well as access to capital and liquidity for vessel owners and operators. The maritime industry is notorious in the great variance in rates and thereby vessel values between good and bad years. Such variation may e.g. force ship owners into bankruptcy. An example is the rates of cape-size bulk carriers [175 000+ dwt]: In December 2008, the lowest concluded contract was at below USD 1000/day (Informant), In April 2007, the rates were at a record USD 104 000/day [60], current rates [June 2010] are about USD 40 000/day [61]. Stopford [2] chapter 3 provides an oversight of the larger cycles between 1741 and 2007.

Internal operations are about vessel operation and the capacities required for this. By law, ships need documentation for reporting purposes, coordination of vessel operation and state of repair. For instance, ships need to be in class and in appropriate condition to be able to operate; if conditions are found unsatisfactory at port inspections, ships may be ordered out of service, with implications to the trades they operate.

Transportation failures is about moving the vessel, including factors such as vessel support functions, crew changes, spare parts, provisioning and the likes. Support functions for vessels are highly dependent of transportation of replacement crews, spare parts when necessary, provisioning and the likes.

Human resources in vessel operations are very relevant for certain sectors. Dangerous cargos need special training and certifications, personnel with such are not necessarily readily available on short notice.

Table 8: Elaboration of failure modes vessels

Vessels	Failure mode: loss of	Elements that may be backed up	Example	Advantage	Disadvantage
Supply	Availability of vessels in market - type, size, characteristics	Vessel; type, size, characteristics. Alternative vessels	Own or long-term lease a fleet	Secured availability of suitable vessels	Cost, increases complexity, may require competencies which are not in-house
Financial flows	Revenues, access to capital and liquidity, for operating and investing in vessels	Ownership, financing, contracts	Insure the vessel voyage against SC disruptions	Compensation in case of disruption, reduce economic loss	Cost, do not cover immaterial value (e.g. reputation), not all risks are insurable
Transportation	The ability to move vessels	Alternative routes,	Choice of routes: avoid high risk areas like Somalia (Norw. Chemical tanker company Odfjell sails around Africa)	Reduces variance in sailing times, reduces risk of hijacking etc.	Cost, longer sailing time, lower fleet utilization
Communication	Coordination and control with other vessels and land	Radio systems, navigational aid	Secondary satellite phone system for communication with shore control	Increase the robustness of ship to land communications	Cost, requires training and protocol
Internal operations / Capacity	Loss of ability to operate vessels, including, including failure of loading gear and pumps	Maintenance levels	Investing in higher maintenance level	Lower risk of vessel found out of class	Higher cost
Human resources	Skilled vessel crew for operation	Crew, certifications, training	Certification program for ship crew: operate without pilots on certain stretches	Ship may operate without pilot: reduce queuing time	Cost for training, time investment.

5. Discussion

Stakeholders wanting to assess their maritime transportation system for LFHI risks are advised to use table 3 to identify the key functions. Their goals should be to prepare to restore the capacity or ability of performing this function. A question for future research is the interaction effects between failure modes; in case of loss of multiple failure modes, how much will this restoration effort depend on the others, and how robust are restoration plans of one failure mode, given that another has also failed? For instance, how much will the restoration of internal operations of a terminal depend on the ability to communicate?

All failure modes identified should be considered for preparation. The approach is that a ‘Business continuity plan’ should be developed for every failure mode. By this, a plan to restore that functionality or capacity should be made, keeping in mind that transportation systems require capacities that are often reliant on external providers and infrastructure –

some things which may not be easily restored in a disruptive event. Mitigation of risks should also be done with an explicit cost focus, to maximize the business impact of vulnerability reduction.

For a full vulnerability assessment, mitigating frequent and operational risks should be included. Through the empirical work, this is the focus of present vulnerability approaches. However, addressing frequent and LFHI risks are not two fundamentally different problems; thereby a vulnerability management framework should include both classes of disruptions. In such a framework, a system description and an explicit cost/efficiency evaluation, as well as rules and procedures for updating the vulnerability assessment should be included.

Transparency in the maritime transportation system is another issue for future research. While visibility through the supply chain has been an issue over the last 20 years, see e.g. Lee et al. [62], visibility in maritime supply chains has received less focus.. While not conclusive, indications given through the case work point to that stakeholders may not be fully aware of the broad system vulnerabilities, and resulting vulnerabilities that stakeholders up- and downstream are exposed to regularly. One such example is that in the port resilience survey; a majority of respondents chose to answer on perceived risks in the area where they operated, although they were given the opportunity to give their views of other parts of the supply chains.

Limitations of the study include that no present implementations have been made, testing the predictive capability of the failure modes. Likewise, the study is qualitative only, and does not rank the importance of the failure modes. Third, dependencies between failure modes are not explicitly discussed, although recovery of one may depend on another.

Focusing on resilience, introducing a systems perspective may prove beneficial. For instance, the United States is heavily dependent on maritime transportation in its international trade; 95% of goods by volume were traded by sea. It is striking how dependent the US port system is on a few key ports. A relevant question is therefore: are some few ports becoming too big to fail?

Most of the research work was done in a US context. It is important to note that operational disruptions are indeed more frequent in Europe and Latin-America (Informant), with smaller countries, more border crossings and higher political risks. The concepts from this paper are applicable to the maritime transportation system in general. Factors such as ownership of terminals are often different, though the principles of operations and functions are similar.

6. Conclusions

Through the failure mode assessment, a structure for assessing and reducing the disruption vulnerability for a maritime supply chain has been created. The method focuses on identifying the key functions that uphold the mission of the supply chain; to ensure the throughput of goods from source to the end user, and to shield the operation from the negative consequences of disruptive events. A key point is that preparing to uphold a limited set of key capacities and functions is a powerful approach compared to preparing for hundreds or thousands of potential disruptive events.

Learning from safety and reliability research may prove to add to understanding supply chain vulnerability. The failure mode approach can be extended to study LFHI disruption risks for a system of ports. Third, the failure mode approach will have to be combined with traditional cause-focused approaches for a comprehensive survey of vulnerability; these are all fields of future research.

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