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Øyvind Berle

Risk and resilience in global maritime supply chains

NTNU – Trondheim
Norwegian University of
Science and Technology

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IMT Report

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To my parents

Abstract

Why did they make birds so delicate and fine as those sea swallows when the ocean can be so cruel? She is kind and very beautiful. But she can be so cruel and it comes so suddenly and such birds that fly, dipping and hunting, with their small sad voices are made too delicately for the sea" - Ernest Hemingway, “The old man and the sea”.

The background of this research, given the central condition that the world is completely dependent on maritime transportation systems, is to understand how these systems are vulnerable towards disruptions, what the consequences are if the transportation systems should break down, and how one may give the systems the ability to restore their ability to move goods after a disruption has occurred.

The mission of the system is to move goods, hence the focus on protecting the mission rather than the infrastructure itself. The prevalence of low-frequency high-impact scenarios; events that have a low probability but may cause great harm to the system, give the ground for why not all efforts should be directed towards preventing disruptions from occurring. Disruptions are bound to occur, how may the systems be prepared to cope with these events?

Cases within transportation of Liquefied Natural Gas (LNG) and humanitarian logistics are used to illustrate the problem and the approach to coping with such problems.

The research part of the doctoral thesis can be divided into five thematic areas:
TA1: Energy security, in particular for natural gas and global LNG transportation systems
TA2: Understanding of maritime transportation system failures, in particular for low-frequency high-impact scenarios
TA3: Methods for systematically addressing how systems fail and how these may be made less vulnerable
TA4: The relevance of maritime transportation systems in humanitarian relief operations, and how to strengthen these
TA5: The interaction between supply chain risk assessment and LNG transportation system optimization

Contributions from the research can be summed up as:
C1: An overview of the critical functions necessary for a maritime transportation system’s ability to move goods.
C2: A framework for systematically addressing vulnerabilities in maritime transportation systems, treating both operational and low-frequency high-impact risks, as well as incorporating cost/efficiency criteria in the assessment.
C3: The insight and understanding of failure and restoration of maritime transportation systems is applicable to humanitarian relief logistics, where the application of principles from commercial supply chain management is immature.
C4: Combining supply chain risk assessment with optimization tools for an LNG supply chain increases the robustness and resilience of the system and thereby the energy security of the recipients, while ensuring efficient resource usage of the supply chain.

Preface

“Cosí tra questa
immensità s'annega il pensier mio:
e il naufragar m'è dolce in questo mare” – Giacomo Leopardi

This thesis is submitted to the Norwegian University of Science and Technology (NTNU) for partial fulfillment of the requirements for the degree of philosophiae doctor.

The doctoral work has been performed at the Department of Marine Technology, NTNU, Trondheim, under supervision of Professor Bjørn Egil Asbjørnslett. During the research period, one year was completed at Massachusetts Institute of Technology, Center for Transportation and Logistics, with Deputy director James B. Rice acting as supervisor.

Financing for the research was provided by the Norwegian Research Council through the MARRISK program and through the NTNU Globalization Program. In addition, the Fulbright Foundation, the Jansons fellowship (“Jansons Legat”) and the DNV fellowship (“DNVs stipend”) provided generous funding for the research exchange at MIT.

Target audiences of this work includes researchers and practitioners within

1. Supply chain risk management
2. Maritime transportation
3. Critical infrastructure
4. Energy security
5. Humanitarian logistics

Acknowledgements

"De var ikke blot de sidste, også de smukkeste, en svanesang for en hel æra. Det måtte en sømand opleve, at stå dèr under de hvide tårne af sejl, i passatens medbør og bagende sol, sidde på nokken af storråen 20 meter oppe og eje hele verden"
- Carsten Jensen, "We, the drowned".

This thesis marks the end of a challenging and rewarding period of my life. I owe a number of people my sincere gratitude for inspiration and good advice throughout the process;

NTNU: Professor Bjørn Egil Asbjørnslett has been my supervisor the last four years, he was the one who convinced me to apply for a PhD position, and he has given me many good pieces of advice as well as a great large number of discussions throughout the process. Also, I would like to thank my colleagues and collaborators; Christian Winge, Edgar McGuiness, Elin Halvorsen-Weare, Erlend Meland, Emmanuel Querrec, Henrique Gaspar, Inge Norstad, Leif-Roar Pettersen, Mohammed Shainee, Oceane Balland, Odd Torstein Mørkve, Pedro Ramirez, Runar Persen, Sergey Ushakov, Siri Solem, Stein Ove Erikstad and Wenting Zhu; for stimulating discussions and the department staff for their assistance in practical problems. I am highly grateful that NTNU chose to fund my fellowship, that the Norwegian Research Council funded the project, and to MARINTEK for hosting me the last four years. Also, I would like to thank anonymous referees for giving valuable feedback to my papers.

MIT: James Rice was my supervisor in the "Port Resilience" project at MIT, I am very grateful for him inviting me to stay at MIT Center for Transportation and Logistics, for excellent discussions on supply chain resilience, and for including me in port visits and surveys. I would likewise thank my colleagues at MIT; Adrien Gasparini, Bruce Arntzen, Chris Caplice, David Opolon, Edgar Blanco, Jarrod Goenzel, John Waller, Jonathan Pratt, Karen Van Nederpelt, Karen Spens, Loic Lagarde, Mahender Singh, Nancy Martin, Roberto Perez-Franco, Shardul Phadnis and Yossi Sheffi; for valuable discussions, as well as the Fulbright Foundation, the Jansons' Fellowship and the DNV foundation for financial support for my stay.

I would also thank my friends and family outside of academia for helpful support, for keeping me in touch with the real world, and for providing distraction from my doctoral research. Not the least, I would like to thank Coffee and The Internet – you two rascals made this thesis happen.

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Abbreviations

APEC	Asia-Pacific Economic Cooperation
CSI	Container Security Initiative
CTL	Center for Transportation and Logistics
C-TPAT	Customs & Trade Partnership against Terrorism
DWT	Dead weight tons
EIC	English East India Company
FM	Failure mode
FMECA	Failure mode, effects and criticality analysis
FSA	Formal safety assessment
FVA	Formal vulnerability assessment
GATT	General Agreement on Tariffs and Trade
HAZOP	Hazards and operability analysis
HL	Humanitarian logistics
HRO	High reliability organizations
IMB	International Maritime Bureau
IMO	International Maritime Organization
ISO	International Standardization Organization
ISPS	International Ship and Port Facility Security Code
MIT	Massachusetts Institute of Technology
NGO	Non-governmental organization
NTNU	Norwegian University of Science and Technology
PHA	Preliminary hazard analysis
QRA	Quantitative risk assessment
RAC	Risk acceptance criteria
SOLAS	Safety of Lives at Sea
TEU	Twenty-foot equivalent unit
UNCTAD	The United Nations Conference on Trade and Development
VLCC	Very large crude carriers (VLCCs)
VOC	Dutch East India Company (Vereenigde Oost-Indische Compagnie)
WFP	United Nations World Food Program
WIC	Dutch West India Company
WWII	World War II

1. Introduction*

"God must have been a ship-owner. He placed the raw materials far from where they were needed and covered two thirds of the earth with water." – Erling Næss

Global maritime transportation systems are essential for the world economy, providing access to energy, raw materials and finished goods to places where these are scarce, needed and wanted. At a glance, one may assume that maritime commerce is a modern phenomenon. Bernstein [1] shows that trade has been essential throughout history, and how maritime transportation has helped form the world we live in.

The title of this thesis, "Risk and resilience in global maritime supply chains", has a modern touch to it, using current concepts such as "resilience" and "global supply chains". However, the essential concepts are not at all new: how societies depend on maritime transportation systems and maritime commerce; how these systems may break down; what can be done to prevent such breakdowns from occurring; what consequences will happen if indeed these transportation systems do break down; and how systems should be designed?

My own story, having grown up in the old Hanseatic trade town Bergen, gave me perspectives on trade throughout history. The medieval wharfs are visible signs of a long maritime tradition, where in particular dried and salted cod was shipped in from the north, and traded onwards to continental Europe. Due to the geography of Norway and lack of roads, as well as the threat of piracy, international trade was more prevalent than trade between East and West Norway. This was visible also in the Viking age, of which remnants still exist; mastering the ocean was possible with supreme vessel technology – great journeys as far as across the Atlantic were made possible. Maritime commerce has impacted the growth of civilizations, and still plays a great, though almost invisible, part in the lives we live.

The following sections (1.1 and 1.2) discuss general characteristics of the shipping industry and the historical development of maritime commerce. Readers should be advised that these sections may be skipped, though they provide an overview and a historical perspective of the domain.

*Sections 1.1 and 1.2 of this introductory chapter has primarily been based on two books; Bernstein's "A splendid exchange" [1], and Stopford's "Maritime Economics" [2]. The thesis format is based on a template by Conradi and Bjørnson [3].

1.1 Characteristics of maritime commerce and the shipping industry

Why is merchant shipping wanted and necessary? I would argue this is due to three reasons: 1) Raw materials are located somewhere else than where these are sought for, and in between there is water. 2) Ships offer the potential to move large amounts of cargo over long distances with little use of labor. 3) Scale advantages allow for more cost-efficient production; to utilize such effects, produced goods needs transportation to markets.

The demand side for maritime transportation can be described through studying the flow of goods. The largest volumes of commodities currently traded by sea can be organized into four categories [2], page 58]:
1) Energy trades, by weight accounting for 44 %, comprising crude oil, oil products, liquefied gas and thermal coal for electricity generation.
2) *Metal industry trades*, accounting for 18 %, including the raw materials and products of steel, such as iron ore, metallurgic coal, various non-iron ores, steel products and scrap metal.
3) Agricultural and forestry trades, in total 9% of volumes, consisting of the raw materials and the products from the agricultural industry. Commodities include cereals such as wheat or barley, soy beans, sugar, agribulks (dry bulks are e.g. seeds, wet bulks are typically oils such as soy or palm), fertilizers and forest products.
4) Other cargos, ranging from industrial materials such as cement to semi-manufactures and manufactures such as machinery and vehicles. While only constituting 29 % of volumes, in value the share of this latter category is closer to 50 %.

The supply side for sea transportation can be classified into three segments [2], page 62]: Bulk cargos, Specialized parcels and General cargo parcels. Bulk cargos can be defined as *"Unpacked homogeneous cargo poured loose in a certain space of a vessel or container"* [4], which are split into dry buck such as coal and wet bulk, such as crude oil. Specialized cargos consist of large parcels with non-homogenous cargos, such as motor cars, refrigerated cargo and liquefied gas. These are transported on dedicated vessels. Finally, general cargo parcels are defined as *"any individual parcel too small to fill a ship or hold"[2]*. These cargos are transported as containerized goods, palletized goods, or stowed goods in cargo holds. Examples of vessels can be found in figure 1. The market for ships, ship building et cetera is not a central theme in this thesis, and will not be discussed further.

Adam Smith gave examples of scale effects in "The Wealth of Nations". For instance, in six weeks sometime in the 18th century, two men and six to eight horses pulling a wagon could carry about 4 tons between London and Edinburgh. In the same time, six to eight men manning a ship could move 200 tons – a labor productivity benefit of 15 times [2]. Such effects are relevant today; the larger containerships currently in operation can carry about 15000 twenty-foot containers [TEU]. This would require 7500 trucks, assuming a 40ft container per truck. More so, assuming a vessel crew of 20, the labor productivity is 375 times higher by sea (naturally, disregarding the support staff needed to dock, produce, maintain and load the vessel, as well as the availability of fossil fuel to power engines).

Figure 1. Example photos. Clockwise from top left: Container vessel with harbor cranes “Eugen Maersk” [5], LNG tanker “Arctic Voyager” [6], Crude oil tanker “Front Ardenne” [7], Car carrier “Alliance New York” [8].

Adam Smith stated that shipping was relevant for the production side too [2]: his example was that ten craftsmen could each make less than 100 pins a day. Combining efforts and specializing, combined they could make 48 000 pins. As this would be too much for a home market, access to transportation and thereby customers was fundamental to utilizing these scale effects. A current example is the usage of 300 000 DWT bulk carriers. Significant infrastructure is required to handle, store and process parcels of a tenth of a million tons of iron ore. However, Chinese shipping companies are considering ever larger bulker designs, at present 600 000 DWT [9], showing that scale effects are indeed relevant.

1.2 History of maritime trade and its development

Growing up in a modern Western country, it is hard to grasp the access to goods from across the world. My local supermarket present perfectly ripe apples from New-Zealand next to Peruvian avocados, pineapples from the Maldives, Spanish oranges and Algerian dates as the most trivial thing. Given the access to such vast amounts of goods in this variety, it is overwhelming to grasp the importance of trade throughout history.

Almost two thousand years ago, a roman laborer would have to pay a year’s wage for a hundred grams of silk [1], barely enough for a scarf – only the wealthiest could afford a toga. Exotic commodities such as silk could be worth its weight in gold, and only these were worthy of being transported around the world. The silk trade followed two main routes: the land route through Asia or the sea route across the South China Sea, the Bay of Bengal, cross the Arabian Sea and the Red Sea, overland through Egypt and finally across the Mediterranean, a journey that would take at least 18 months, see figure 3.

Normally, goods would change hands a number of times throughout the journey as traders followed their goods only for limited stretches, there was little oversight throughout the chain. As a result, little was known about the origins of trade goods such as spices, neither the origin nor exactly how it would be produced. It is safe to assume that the lack of such knowledge increased both the exclusivity of the good, as well as in some instances its healing power used as a medicine. This phenomenon is still visible in current organic health food stores.

Before the arrival of the European Caravel in the 15th century, valuable sea-borne cargo would be rowed; sailing was reserved for low-value cargo. A 150 feet trade galley could carry up to 500 oarsmen, not including other crew, officers and passengers. Late Venetian galleys would carry up to 300 tons of cargo.

Maritime commerce has been relevant all through the development of civilizations. In the following sections, maritime commerce is illustrated, in particular in the light of the vulnerability and struggle for control of these trade routes.

1.2.1 15 000 - 10 000 BC

The time when man started creating watercrafts is unclear. Cave paintings and some maritime remains indicate that simple boats created for hunting emerged in Northern Europe about fifteen thousand years ago [1], page 22]; a major weakness of the reindeer was that it had poor abilities for swimming, requiring it to hold its head high for breathing – this made them easy targets for humans. Simple boats made from animal hides sewn over antler horns were used for hunting. The advantage of moving the carcasses by boat compared to by land must have pushed for using boats for other types of cargos.

One of the earliest traded commodities must have been obsidian, a volcanic rocklike glass that could be chipped razor sharp cutting tools and weapons [1], page 23]. For archaeologists, obsidian is relevant for two reasons: It is only to be found in a limited number of volcanic sites, and that samples can be traced back to its source. Obsidian flakes dating twelve thousand years back found in the Franchti Caves on the Greek mainland originated from Melos, an island some 160 kilometers offshore. This indicates that there has been maritime movement of goods, although no historical evidence exists to give more insight in this trade.

1.2.2 4000 BC – 1450 AD

Herodotus described the earliest of large cargo ships used for trade down the Euphrates to Babylon [1], page 24]; wooden frames supporting a skin of sewn hides could carry up to fourteen tons. For the reason of strong currents, the boats could not be paddled upstream, so upon arrival to Babylon, the wood frames would be scrapped and the hides packed on donkeys for the return upriver. Then, a new vessel could be constructed from the same hides. The origins of this trade is about six thousand years ago, where copper was shipped from the Ergani mines in Turkish Anatolia to Uruk (160 km west of Basra) in what is now Southern Iraq.

With the arrival of written records about 3000 BC, we may get a better perspective on the extent of maritime commerce [1], page 26]. Dilmun, the land of milk and honey in the Sumerian creation myth, not far from current Qalat al-Bahrain, was a major trading center for copper from current Oman. What is relevant is that the settlement had about 5000 inhabitants, which is far more than what could be sustained from the agricultural hinterland. Hence, the town was reliant on grain imports from upriver Euphrates. Around year 2000 BC, it is expected that the shiploads were in the range of several hundred tons, being the lifeline of the town. In effect, already 4000 years ago societies were entirely dependent on maritime transportation.

While the cradle of civilization in Mesopotamia, including the Sumerians, Akkadians, Assyrians and later the Babylonians, had access to enormous grain resources allowing them to settle down and free labor for other tasks than hunting and gathering, they had little other strategic materials such as metals, timbers and even stone [1], page 28]. As much of the modern world depends on oil imports, the trade of these goods was vital for these empires – the large volumes despite doubtless enormous transportation costs illustrate the significance of these goods.

The reliance on food imports can explain the pattern of growth of the Greek empires. While the first human civilizations settled in some of the world's best farm land between the rivers of Euphrat and Tigris (current Iraq), and on the banks of the Nile (Egypt), this was not the fact in Greece. A traditional Greek farm could not even grow grain for its own needs [1], page 46]. All the while, the production of wine and olive oil for trade allowed for both food to feed the populace, as well as time and resources for farmers to participate in military service as Hoplites.

Grain imports to Greece came from three sources, as illustrated in figure 2. Before 600 BC, Egypt was the main source. From around 800 BC, however, Greek colonists started settling the eastern coast of Sicily - the colony of Syracuse, as well as the north shores of the Black Sea, what is now Southern Ukraine. Due to geography, the Spartans and their allies got their provisions from Syracuse, while Athens and its allies sourced grain from Ukraine – these two cities were the main adversaries of the Greek cities.

Figure 2: Athenian Grain Routes (based on [1] and [10])

It is relevant to observe how vulnerable these sea routes were, both passing through narrow seaways with ubiquitous risks of attacks from pirates and rivaling cities: Ships following the eastern route also had to pass the straits of the Dardanelles and Bosporus, which were settled and fortified from around 660 BC to respectively protect and prevent the trade [1], page 48]. Before the magnetic compass, the navigation season in the Mediterranean only lasted between May and September, as rough sea and cloud covers prevented open-sea transit for the remainder of the year.

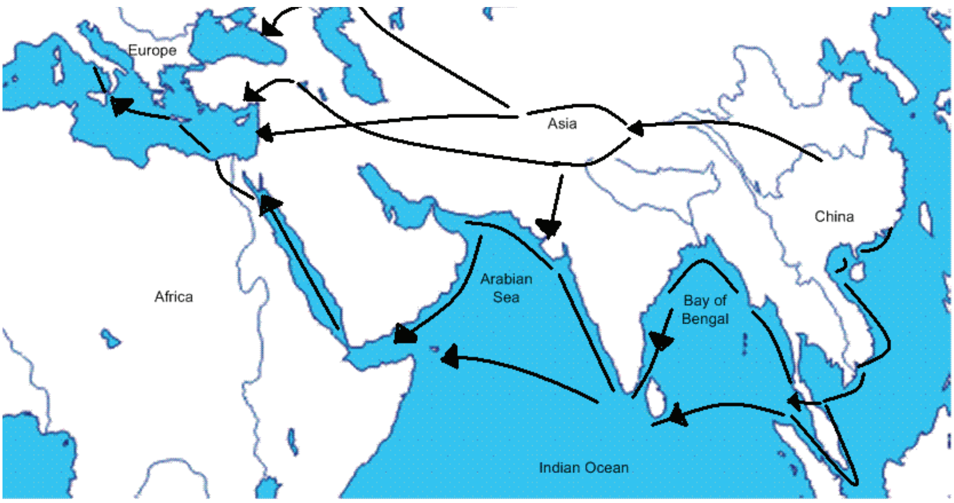
The Greek import dependency and the struggle for control of these sea routes and food sources led to a number of large battles. By 450 BC the Athenian navy patrolled the black sea more or less continuously, a move at the time unheard of in history [1], page 49]. As neighboring city-states were just as dependent on these supply lines, requiring protection from "barbarians" and pirates, they soon joined forces with the Athenian, leading to the Athenian Empire. However, the Peloponnesian War started, like World War I, with a minor conflict in 431 BC, growing into a major Greek war. Between 415 BC and 413 BC, Athens decided to cut off the supply routes to Sparta by breaking the supply lines from Sicily. A surprising defeat led to the destruction of the majority of the attacking fleet, leaving Athens vulnerable against attack. In late summer 405 BC, the counterattack came, taking or sinking the majority of grain ships. An invasion of Athens was no longer necessary, leaving the city to starve: Athens would never again regain its former position.

Athens, as the cradle of Western civilization, illustrates the example of Western naval strategy [1], page 51]. Venice followed suit in the 1200s, then Holland of the 1600s and England of the 1800s: All nations had outgrown their domestic supplies, and depended on trade and imports for both survival and wealth. Comparing this with the current case of oil import dependency of the Western world gives perspectives on the battle for control of oil resources in the latest century, and the US reliance on its navy.

The growing relevance of the Chinese can also be observed as the battle for resources increases. Chinese companies take increasing control of resources in the Middle East and in Africa. As for the other empires, to protect vulnerable sea routes of transportation, China is growing its navy fast, leading to worry among existing powers [11].

The history of the Roman Empire, from about 500 BC to 500 AD can explain swaths of the growth of global trade. Not unlike the luxury trades, the more exotic the goods, the more attractive it was. The importance of silk as a global merchandise has been illustrated earlier. Its main trade routes from China were the Silk Road and the sea routes around India [1], page 3]. The overland route based itself on camels (the preferred pack animal from around 1500 BC), where one driver would lead three to six camels, carrying in total between one and two tons of goods [1], page 56]. Given the camels' capacity to go three days without water and an average day's journey of around 50 kilometers, trading posts (Caravanserais) were located about 150 kilometers apart throughout the Asian steppes.

Figure 3: The spice routes from China to Rome, the silk road and the Monsoon routes (based on [1] and [10])



Until pepper and silk arrived in the West, incense was the most important commodity. Already in 3500 BC, it was consumed in Babylon and Egypt [1], page 59]. The primary sources were current Yemen and Somalia, the supply chain went either by ship through the Red Sea or overland on camel through the Arabian Peninsula – the latter route considered safer due to frequent piracy and weather challenges. At the peak of Roman incense imports around 200 AD, ten thousand camel loads of incense was shipped to Rome every year [1], page 66] together with silk significantly draining the coffers of the empire.

Naturally, walking overland throughout Asia with camels was a perilous journey. In particular, tribes controlled the Arabian Peninsula, lacking a central authority. In this, a major source of income is raiding the trade of neighboring tribes. Academically, this may be described as a typical case of sub-optimization, where parties had a large incentive in gaining a larger share of the trade revenues, rather than actually performing trade. This was to change with the rise of Islam.

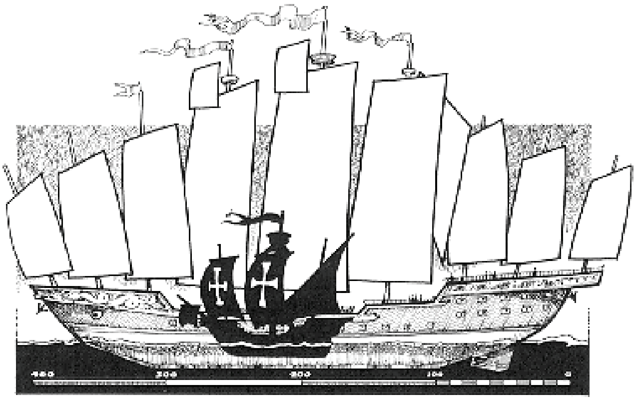
Mohammed was born in 571 AD, and raised by his uncle, a trader. Trade and Islam was strongly connected, as illustrated by the Koran, Sura 4:29: "O you who believe! Do not devour your property among yourself falsely, except that it be trading by your mutual consent" [1], page 71]. In this, the growth of Islam can be understood as a bubble of unity against the unbelievers, where Islamic traders were protected and "infidels" preyed upon. Through a combination of conquest and by providing strong incentives to convert, by 750 AD, the Muslim empire recreated a Pax Romana throughout large parts of Asia, effectively controlling trade. In addition, Muslim navies took control of the East Mediterranean in 655 AD and later the remainder of it, effectively shutting down sea trade between East and West until Vasco da Gama's arrival in the late 1400s.

However, the eastern sea trade was blossoming, led by the Arabs, Persians, Indians and in particular the Chinese. The gradual collapse of the Abbasid Empire in the 800s and 900s made the overland trade routes more dangerous. However, the trade winds in the Indian Ocean allowed for easy trade by sea. In the AD 1000s, the Chinese Song Dynasty shifted their focus towards the sea, resulting in the establishment of a permanent navy in 1132 [1], page 98]. The Chinese vessels carried innovations such as iron-nailed vessels with several decks, the magnetic compass and sails that allowed for tack courses.

The most famous Chinese sea voyages were the seven voyages of the treasure fleets, commanded by the eunuch Zheng He between 1405 and 1433. Most of the voyages consisted of about three hundred vessels ranging from 100 feet "support ships" to nine-masted 3-400 feet "treasure ships", as well as a crew of about thirty thousand [1], page 100]. Objectives of the mission were diplomatic, military and symbolic, rather than commercial. The primary achievement of these voyages was the stabilization of the Strait of Malacca, connecting the Indian and Pacific Oceans and separating Peninsular Malaysia from Indonesian Sumatra. This is still considered one of the vital chokepoints of maritime commerce. The vessels reached as far as much of the East African coasts.

Due to a power struggle between the Confucian bureaucracy that loathed trade, and the eunuchs, controlling most of it, no more trading missions would follow. Neither the commercial nor naval Chinese fleet was given any priority. In 1500, the emperor made building vessels with more than two masts a capital offense, followed by a 1525 decree making any oceangoing vessel illegal, effectively ending Chinese maritime presence. However, seeing how the goals of the expeditions never were commercial profit, who can blame the emperor for setting down the foot to excursions costing half the industrial output of the country?

Figure 4: Ming treasure ship and Columbus' Santa Maria [12]



As for Central Asia after the decline of the Umayyad and later Abbasid empires, the Asian waters without patrolling navies soon was full of pirates. Fortunately for the Portuguese explorer Vasco da Gama's ego, he arrived in the Indian Ocean 65 years after Zheng He's voyages ended. Da Gama's largest caravel São Gabriel at 27 meters was on par with the smallest vessels in the Chinese fleet.

As incense had been the most sought-after commodity in antiquity, spices such as black pepper, cinnamon, nutmeg, mace and cloves took this role between the 1300s and the 1600s [1], page 110]. Venetian and Genoese merchants could buy spices in the markets in Alexandria and sell them in their home markets for three to five times the sum, giving them net returns in excess of 100% after shipping, insurance and customs. Europe, having little goods of interest for the Eastern partners, resorted to slave trade for the Muslim armies. Their main sources of slaves were in the eastern parts of the Black Sea and selling them in Egypt and the Levant (east coast of the Mediterranean). As for the Greek grain supply chains two thousand years earlier, this trade was absolutely dependent on the waterways through the Bosporus and the Dardanelles, then controlled by the declining Byzantine Empire. The conflict between Venice and Genoa led to a number of battles, whereof these straits were one. (Venice took Constantinople in 1202, Genoa toppled the Venetian rule in 1261, the slave trade was greatly reduced in 1292 with the fall of Tyre and Acra, re-establishing land based trade of slaves from Caucasus. 1, p127)

An observation here is: What do Chinese eunuchs, Muslim slave armies and catholic priests have in common? This could either be the start of a really promising joke or an interesting academic debate. We will focus on the latter. Francis Fukuyama [13] argues that three elements are needed for successful state building; a strong state, a working legal system and mechanisms for holding the rulers responsible. To control large empires, it was critical that nepotism were controlled, as favoring family is indeed human nature. Hence, the eunuchs could not procreate, so their offspring could not be favorites. Slave armies served to free themselves, not for their families. Catholic priests were forced into sexual abstinence, hence removing their possibility for having offspring that could challenge the existing power structures.

Trade in Northern Europe expanded throughout the middle age. Bruges in Belgium became one of the new trading centers in the years after 1227, taking over the position as a leading trading power within Europe [2], page 11]. Europe's need for raw materials such as wool, timber, corn and fish led to the establishment of a precursor to the Hanseatic League in Lübeck in 1241 – the first official meeting of the League was held in 1356. The Hanseatic League can be seen as a precursor to the European Union, with its common commercial practices, currencies and institutions. Its final collapse in 1669 can be explained to be due to its clumsy structure, the rise of new rivals, and the impact of the Reformation [14].

1.2.3 1450 - 1833

The Ottoman capture of Constantinople in 1453 shut down the remainder of Muslim - Christian spice trade [1, page 129]. However, the battle for the spice trade had started earlier, Venetian and Genoese merchants had strong commercial interests in the crusades; the battle for control of the enormous cash flow of the Spice trades provided strong incentives for continued efforts in the crusades. The Muslim control of this trade led to several efforts by other powers to find a sea route to India. Portuguese King Henry the Navigator greatly supported map making and maritime development, leading to the discovery of the Caravel and later its larger sister the Carrack ("Nau" in Portuguese). These weatherly ships were sturdy enough to handle the strong winds of the ocean, as well as that their rigging allowed for tack courses. (See illustrations of Columbus ships in figure 5).

Much can be said about Christopher Columbus' estimates of the distances between Lisbon and India, the goal for the European spice expeditions. Already 1700 years earlier, in 205 BC, Greek Erastothenes of Alexandria calculated the circumference of the Earth [1, page 164]. Funded by the Spanish Queen Isabella and the Spanish finance minister Luis de Santangel, Columbus departed west in 1492, where the discovery of the Americas is history. As the scholars of the Spanish court were more enlightened about sailing distances than Columbus, the discovery of a world only briefly described by the Vikings, came as a great surprise. The pillaging of which in the following centuries led to unimaginable wealth in Spain and immense suffering in the New World.

Figure 5: Columbus ships; Caravel “Pinta”, Carracks “Santa Maria” and “Niña” [15]

Vasco da Gama’s expedition to India between 1497 and 1499 had a more solid scientific foundation than that of Columbus [2]1, page 170] and was based on two “innovations”. First, a recent discovery of the last decade, northbound trade winds led him to do a great circle sailing almost to Brazil after the Cape Verde islands, before circling south towards the Cape of Good Hope – a ninety-five day sea journey, where measured latitudes never were more than two degrees off. The second was the use of (kidnapped) Indian pilots to navigate the Indian Ocean. His commercial planning was however limited: they had not brought trading goods for acquiring spices, and local traders were unimpressed with the Europeans. Likewise, cultural sensitivity was not a strong feature, creating numerous enemies for him. Due to scurvy on the return leg, less than half of the 170 men he set out with got to return to Portugal. However, due to favorable prices of the limited textiles they had brought and cheap spices, the returns was sixty times the cost of the expedition, starting a new era in Portuguese seafaring and brutal conquests in the Indian Ocean.

The reliance on maritime chokepoints made the Portuguese attempt to control Aden and later Bab-el Mandeb (the entrance to the Red Sea), which finally failed in 1538 as the Ottoman Empire took control of Aden. However, in 1511, the Portuguese took control of the Malacca Strait, which was critical to the Spice trade, originating from the Maluku (Spice) Islands in Indonesia [2]1, page 184] In spite of this, due to limited manpower, Portugal never managed to fully monopolize the spice trade; Ottoman trade with Venice, then France and the German countries took part in watering out their dominance. As Portugal (in what Bernstein refers to as “in a proud Iberian tradition”) focused on military control rather than trade, it was continuously broke and gradually lost relevance from the mid 1500s. A relevant academic question is whether the same is happening for the Chinese and Americans in current global trade, where the former bases itself on commerce, the latter of military domination.

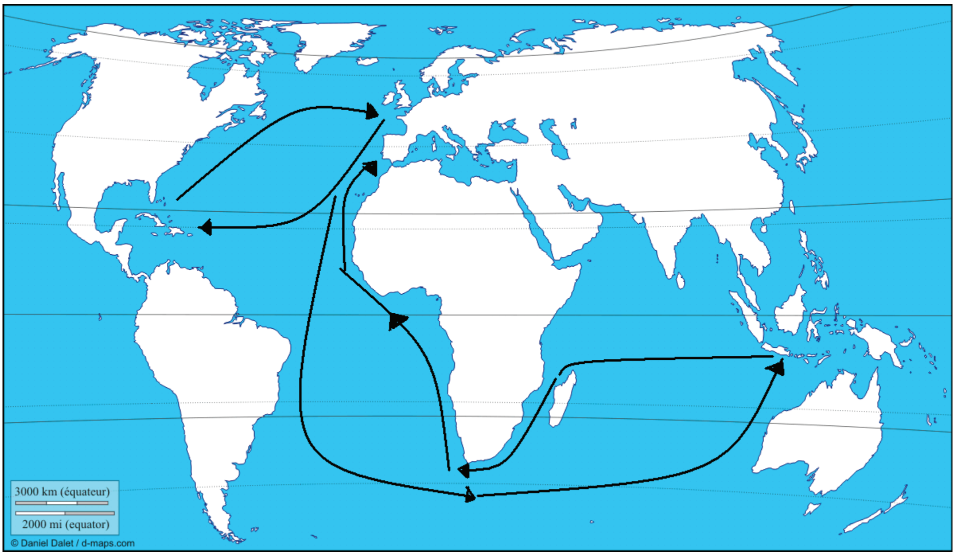
Bernstein [2]1, page 199] points out four factors that led to "globalization" as we know it today:

1) Within a few decades of Columbus voyage to the Americas, the exchange of agricultural crops such as corn, wheat, sugar and coffee had revolutionized the world trade and labor markets.
2) By the early 1600s, Spanish and Dutch sailors had revealed the Earth's wind patterns, allowing for crossing the oceans.
3) Vast silver deposits discovered in Peru and Mexico allowed for a global monetary system, the Spanish eight-real coin (named dollar after 1690), in effect from the 1500s to the 1800s.
4) The rise of the joint-stock corporation, with a number of advantages compared to royal monopolies or single families.

Between 1577 and 1580, Francis Drake, in command of "The Golden Hind" repeated Magellan's 1519-1522 circumnavigation of the globe. Returning to Plymouth harbor, he carried pirated Spanish silver and gold (supposedly so much that it replaced the ballast of his vessel) and Dutch trade goods, as well as cloves and nutmeg from the Spice Islands. After the plundered Spanish riches were handed over to the crown, the voyage paid returns fifty times the cost. More important, he carried the Portuguese pilot Nuño da Silva, maps and the knowledge of celestial navigation in the southern hemisphere [2]1, page 215]. Cavendish repeated the feat in 1588, returning with Spanish loot, crew clad entirely in silk, gold lined sails and the main sail made entirely from damask. Such riches provided strong incentives for further expeditions, leading to the establishment of the English East India Company (EIC) in 1600.

The Dutch East India Company (VOC) was incorporated in 1602 with a 21-year monopoly on Dutch Asian trade. Nine years later, in 1611, Captain Brouwer of the VOC took a southeast turn after passing the Cape of Good Hope, rather than the usual turn northeast towards India [2]1, page 210]. In this, he became the first captain to ride the Roaring Forties, the strong westerly winds normally found between 40 and 50 degrees south, all the way to Southeast Asia. This became the trucking road for European navigators for the next three centuries. After the north turn for the Sunda Strait, Bouwer reached current Jakarta in five months and twenty-four days after his departure from Holland, achieving two goals: The route was over twice as fast as the contemporary route, and he completely avoided the Portuguese at Malacca.

Figure 6: The sailing patterns between Europe, Asia and the Americas (based on [1] and [10])



Both the VOC and the EIC were allowed to conduct military operations (on certain terms of loyalty) – and were dependent on doing so to protect the trade routes. Between 1602 and 1663, The VOC with its sister company the West India Company (WIC) effectively ran a world war, fighting for sugar in Brazil, spices in Asia and slaves and gold in Africa. The largest success of the VOC was though as a commercial enterprise. Dutch financial systems were the most advanced in the world in the 1600s [2]1, page 223], offering an effective capital markets, bonds and futures, maritime insurance and fractional ownership of ships and companies – all of which stimulating commerce. In the 1620s, the interest rate in Holland was 4%, in England 10%, allowing the Dutch to borrow 2.5 times as much money. This allowed both merchants to invest in commerce and the state to fund its military.

To control the spice flows; in 1605 the VOC decided that it needed not a monopoly of trade to Holland but to the world. As a consequence, they decided to take control over the Spice Islands, the origins of the spices located in the Maluku archipelago in present Indonesia. After a number of bloody battles, the VOC finally signed a peace treaty with the Spanish in Münster in 1648. The result of which was that the VOC could significantly increase the scope of its commercial operations [2]1, page 222]. The most profitable routes of the VOC was in fact the intra-Asian trades; Spices from Indonesia; Gold, copper and silver from Japan; tea, porcelain and silk from China, and Indian Cotton all went trough Batavia (current Jakarta), the main trading post of the Dutch. Only the most valuable cargos actually crossed the Cape. The Dutch Golden age ended with shifting tastes of the Western consumers, combined with new focus areas of the English. The new major commodities included cotton from India, tea from China, sugar from the Caribbean, Coffee from Yemen and Indonesia, and slaves from Africa [2]1, page 240]. The cynical nature of the latter trade in part led to the US civil war.

The triangular trade of the 1800s Atlantic basin is taught to any school child in the West; Commodities such as sugar, rum, cotton and tobacco from the Americas to Europe; manufactured goods such as textiles from Europe to Africa; Slaves from Africa to the Americas. This is an oversimplification that neglects the short haul trades – however it does illustrate the flow of goods [2]1, page 278]. The Eastern trades were not as simple, in particular as no obvious trade goods could be found to match the demand for goods such as tea. Until about 1820, tea was traded with Indian cotton in China, the cotton for manufactured goods from England, and tea to England [2]1, page 287]. Due to increased domestic production of Cotton in China, this trade broke down; the EIC had to pay for the tea with prized silver.

To understand where Adam Smith got the inspiration for his free-trade manifesto ”An Inquiry into the Nature and Causes of the Wealth of Nations” [16], one must understand the context of English trade and mercantilism. The EIC gained from its monopoly on trades to the East, while suffering from domestic protectionism in textile manufacturing [2]1, page 283]. Smith's theory about the "invisible hand of the market" was directly opposed to the state monopolies; he argued that the government should facilitate a multitude of parties competing. This also became a case with parallel trade.

Opium sourced from India became the sought-after trade good for the British to China. Its use had first been made unlawful in China in 1729, so the EIC could not directly sell it in China – it had to go through local smugglers for fear of the wrath of the Chinese Emperor. Bernstein argues that the myth of the "entire Chinese population" being opium addicts is a gross overstatement. While half the men and a quarter of the women were occasional users, by 1879, less than one percent inhaled enough to be at risk for addiction [2]1, page 290]. Arguably, silver and the trade balance was as important a cause for moral outrage as the consumption of opium. Like now, the illegality of the trade forced prices up – the high prices paid for drugs in Western countries now finances one of the world's largest industries, the "war on drugs" is a seemingly futile game only benefiting drug lords. Around 1800, the trade balance was heavily favoring China. According to EIC records, the tides turned in 1806, and by 1820, a fifth of the value of Chinese exports was silver. In 1834, the EIC finally lost its monopoly of trade to China [2]1, page 295]. Several confrontations between opium traders and the Chinese authorities finally led to the first of two Opium Wars, lasting from 1839 - 1842 and again 1856 - 1860.

1.2.4 1834 - 1950

Four inventions changed international commerce in the 1800s [2], page 23]:

1) Steam engines allowed vessels to move without wind, significantly decreasing transit times.
2) Iron and later steel hulls allowed for building larger ships which protected cargo better.
3) Screw propellers made merchant ships more seaworthy and more efficient (compared to the earlier paddle-wheels).
4) Deep sea cable networks allowed traders and ship owners to communicate across the world in a matter of hours rather than months.

The speed of international trade growth illustrates the massive changes in global commerce. Volumes went from 20 million tons in 1840 to 140 million tons in 1887, averaging 4.2 % annually. Average sailing distances went up similarly, as trade routes within the Mediterranean were replaced with long haul routes to the Americas and Australia. The passenger trades went up similarly, in particular as a function of emigration from Europe to USA and Australia: On average, 32 000 passengers left Europe yearly between 1825 and 1835, 71 000 per year between 1836 and 1845, and a staggering 250 000 per year between 1845 and 1854. Monuments such as the Statue of Liberty in the seaward approach to New York have been closely associated with this migrant movement, and large Italian and Irish communities in cities such as Boston and New York bear witness to this migration.

Shipping regulation became an issue in the 1800s. Lloyds Register had been started in the 1760s as a ships registry, assumed the role of setting standards and classing ships [2], page 34]. Lloyds originally started as the first modern maritime insurer in 1688 in Edward Lloyd's coffee house [17]. Several other countries launched their own classing societies in the 1800s, including Det Norske Veritas (DNV) and The American Bureau of Shipping [2]. Great Britain controlled about half the world fleet in the 1800s. As a result, the majority of maritime legislation in other countries was based on the British standard, leading to a relatively consistent maritime legal system worldwide.

Both liner routes and tramp shipping was well developed by the end of the 1800s. Liner services spread throughout the world as of 1870, accommodating a mix of passengers, mail, general cargo, oils and refrigerated cargo. By the 1950s, there were 360 liner conferences (in effect, legal price fixing meetings) for the deep-sea trades, each with between 2 and 40 members [2]. Tramp shipping in the 1800s consisted of ships moving from port to port, depending on where the best rates could be obtained. This was coordinated via overseas cables from the London ship broking companies through the Baltic Exchange – in 1869, Clarksons spent more on telegram fees than on wages. Compared to the liner services, tramp shipping was dominated by smaller players; a third of British companies in 1912 had less than three ships. Beside the British, Greek and Norwegians were the largest players.

Trade wars, tariffs and duties drove several large changes throughout the between the 1600s and 1800s. In Britain alone, no less than 127 Corn Laws were introduced to micromanage the trade of grains (referred to as corn) – mainly to protect the income of the landowners (who, coincidentally also controlled the parliament) to the disadvantage of the people [2]1, page 301]. The most draconian law, completely forbidding grain imports was implemented in 1815, causing hunger and economic stagnation. These laws have become examples of mercantilism, the debate between Thomas Malthus and David Ricardo has also become a text-book example in international economy on competitive advantages. High food prices forced people to spend a bulk of their earnings on food rather than manufactured goods, thereby costing jobs in manufacturing and more economic loss [18]. The laws were finally repealed in 1846.

Import tariffs were also an important seed for conflict between the Northern and Southern states in the US; before the introduction of income taxes in the 1900s, import duties financed 90 % of the US government [2]1, page 320]. The North demanded protection from British manufacturing; the South did not want their farming exports touched. In 1833, the "Compromise Tariff" passed the US Congress, thereby delaying the civil war for a generation. The 1861 - 1865 US Civil War was about tariffs, but also about slavery and states' right: the Northern (Union) side won over the separatist Southern (Confederate) states.

The transition from wooden sail ships to metal steam ships took almost a century, due to several reasons. One was the cost and cargo capacity needed for fuel; ships using more than 25% of its cargo capacity for fuel would not be competitive. By 1850 sail ships were more economical beyond 4 800 kilometers, by 1890 beyond 16 000 km [2]1, page 328]. In the early 1900s, only low-value long-haul cargos such as guano and dried cod were transported by sail ships. Other problems were the fouling of iron hulls, and that steam ships cost 50% more to build and needed 50% more crew. Also, the availability of cheap American timber and the precise meteorological charting of the earth's wind patterns kept the sail ships competitive. However, the opening of the Suez Canal in 1869 cut the sailing distance between Europe and Asia from 18 000 kilometers to 10 500 km, thereby removing one of the most important routes for sailing ships. China's main export to Europe was tea, of so high value that shippers were willing to pay extra charges to ensure fast delivery.

As shown, not everyone benefits from trade. European farmers were hurt by the enormous farming capacity developed in the Americas and Oceania. Technological innovations led to lower shipping costs, refrigeration technology allowed for a wider scope of goods to be transported. The Swedish economists Heckscher and Ohlin, the last of which won the Nobel Prize for this theory, that trade and decreasing shipping costs led to global convergence of commodity prices, as well as the input factors; wages rents and interest rates [2]1, page 340], which has been proved as a robust result [19]. The Stolper-Samuelson theorem explains who wins and who loses from international trade (the owner of the most intensively used input wins), and the implications of this on international trade. In sum, this led to a backlash; the European free-trade movement was set back, according to Bernstein [2]1, page 337], contributing to two world conflicts and present globalization battles.

1.2.5 1950 –

Tramp and liner services had seemed a robust mechanism for a century; few had expected anything but these trades to continue. However flexible, the systems were too labor-intensive; rising labor cost after World War II forced companies to increase the scale of operations, to integrate maritime transportation into larger logistics systems and to invest in labor-saving technology, such as more efficient cargo handling (compared to stowing the goods manually) [2]. Bulk goods were moved by dedicated carriers between terminals designed to handle the goods, general cargo by container ships. Passenger liner routes were eradicated and ships broken up or converted into cruise liners.

The world commerce markets changed with new trade strategies of Western nations after World War II. Increasing protectionism, culminating in the US Smoot-Hawley legislation and retaliation by US partners led the world into autarky [2]1, page 353]. The Bretton Woods conference in 1944, and later the 1947 General Agreement on Tariffs and Trade (GATT) meant opening of economies, including former colonies, and increased trade world wide [2]. The US had also learnt that trade wars in part could contribute to real war [2]1, page 356], as seen in part with the case of Germany, where trade wars offered “an excellent opportunity to arouse popular resentment”. Analogously, within Europe, the Coal and Steel Community was established in 1951, which was expanded into the European Economic Community in 1957 [20] (The current European Union). The motivation was that “tying countries together politically and economically is a way to consolidate democracy and resolve the traditional causes of conflict”

Worldwide sea trade grew from 500 million tons in 1950 to 7 billion tons in 2005 in what Stopford calls “Shipping’s industrial revolution” [2]. In the last half of the 1900s, vessel sizes grew massively, and a number of new ship types were developed, including roll-on roll-off carriers, container ships, liquefied gas-carriers and chemical tankers.

The growth of the bulk shipping industry was driven by multinational corporations. Until the 1950s, international oil trades were limited; oil was normally transported as products in smaller tankers. Strategies changed into moving crude near the markets to refine it close to customers, creating a market opportunity for larger vessels [2]. Steel mills similarly moved closer to shore, while iron ore and coal mines were developed overseas to supply them. Hence, commodities like oil, iron ore and coal were used in such large quantities that parcel sizes well above 100 000 tons were practical. Until the 1950s, normal vessel sizes were not above 10-12 000 tons. For dry trades, by the 1970s, vessels over 200 000 tons could be used for high-volume routes, similarly over 300 000 by the 1980s. The average crude tankers correspondingly moved up to being around 80 000 dead weight tons (dwt) by the 1980s, the average size stabilizing there. Very large crude carriers (VLCCs) are now around 300 000 dwt, where the extremes built in the late 1970s were around 550 000 dwt.

Container shipping technologies turned the liner shipping industry completely around. Developed in 1956 by Malcolm Mc Lean [2]1, page 361], over the next centuries it made general cargo trade virtually free. By the 1960s, port congestion and labor difficulties were significant bottlenecks; cargo from Europe to the US could take months to arrive [2]. In comparison, a container could arrive in the US only days after being sent; ready to be transferred to rail services going inland. Containerization covered a wider perspective than just moving general cargo: by investing heavily in infrastructure, an end-to-end responsibility of cargo was made possible within a closed conference system.

Current shipping markets are characterized by ever lower shipping costs [21]. The cost of a transatlantic shipment of a 20 foot container, which can carry up to 15 tons of goods, is comparable to an economy class plane ticket. Transportation of a crude oil from the Middle East to the US cost less that 1 US Cent per liter. A ton of iron ore from

Australia to Europe runs less than USD 10. Sending consumer electronics from Asia to Europe would cost USD 10 for a TV set and USD 1 for a vacuum cleaner. In other words, the transport cost is marginal compared to the product price – which is quite the development since the origin of international trade.

The present focus of ever reducing cost on transportation, combined with increasing societal dependence on maritime transportation, makes this an interesting subject. The relevance of the subject is shown in the next section.

1.3 Current relevance of sea trade systems

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 [22] 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 contend that existing research on ports in a business perspective is modest [23]. Robinson similarly suggests that ports should be included as elements in value-driven chain systems [24].

The current dependence on maritime supply chains can best be illustrated by when these fail. Extreme examples are the 1995 Kobe earthquake [25], and the 2002 Los Angeles dock workers' lockout [26], both with massive consequences to business and infrastructure. It is relevant to observe that these events hurt the port element of the supply chain. The Port of Kobe suffered severe damage, 0 of 35 container berths and only 9 of 186 berths total were operable. It took over two years to restore full capacity [25]. Consequently, the port dropped from being the 6^{th} to the 17^{th} largest container port in the world. Long-term traffic loss endured beyond the restoration of port facilities due to the competitive situation in the area, increasing the economic loss endured by stakeholders and dependents of the port.

The 2002 11-day shutdown of US West Coast ports resulting from the lockout of potentially striking dockworkers, as reported by Park et al. [27]. They show that the total losses to the US economy from the incident were about $3 billion, which is severe, although smaller than earlier estimates of 2 to 6 times this number. Stakeholders of the industry thereby have strong economic incentives in avoiding the consequences of supply chain disruptions.

As for the ancient Greek and onwards throughout history, trade has been relying on a limited set of routes. While ships can, in theory, travel anywhere on the oceans, major trade routes follows the shortest sailing paths, referred to as sea lines of communication. Narrow points in these, due to land, islands or shallow water, can be described as chokepoints. While numerous of these exist, only a few are of major importance to world trade, as may be seen in table 1. Sea lane security was an important research topic in the 1970s and 1980s, particularly within a military context [28]. While concern has abated since the end of the Cold war, the subject is as critical as ever with the growth of and dependency on global maritime trade. Maritime transportation is a prerequisite for global trade, as over 80% of global trade in goods are transported by ships [29]. A general trend is that world merchandise trade grows two to three times faster than the world economy, represented by the global gross domestic product. 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.

While chokepoints of sea lanes in theory are a resource of fixed supply, the effective supply is variable. For some trades, like crude oil, pipelines, either origin to destination or parallel to chokepoint, may offer additional transport capacity. Supply may be threatened in two dimensions: physical constraints that restrict transit and actions by states or non-state actors that threaten or restrict free passage [28]. Current threats are not so much direct threats, in the form of military power, as indirect, such as piracy, terrorism, collisions blocking waterways and regional instability. Examples of disruptions include the laying of sea-mines in the Strait of Hormuz in the 1980s, piracy and terrorist attacks in the Malacca Strait, the closure of the Suez Canal between 1967 and 1975, and the terrorist attack on USS Cole near Bab-el-Mandab in 2000.

For my thesis, the initial approach focused on the sea transit element of maritime supply chains. As a part of this, initial discussions were held with the Royal Norwegian Navy and the Norwegian Naval Academy. However, an insight that emerged was that stakeholders assessing their supply chains should focus on factors which they may control and influence. Securing ocean transit is typically the task of national states and supranational organs such as the UN. Also, the ocean transit is only a part of the supply chain, the interaction between sea and land supply chains became a focus for the remainder of the research.

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 [30]. 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 [31, 32]. 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 [33].

Global energy dependence is an illustrating example of the world's dependence of long and complex supply chains. While this study only outlines the problem, it is clear that research is needed to determine possible disruption sources, as well as how participants and dependents of the value chain may adapt and prepare themselves to handle such low-probability high-impact scenarios.

The World Economic Forum (WEF) in their 2008 Global Risk Report identified four emerging global risks: Hyper-optimization and supply chain vulnerability, and energy supply security were two of them [34]. Integration of regional economies has come as a result of reduction in trade barriers and improvement in global logistics and technology. A result is that international and intra-regional trade growth rate has surpassed the global economy growth rate over the last twenty years. The above mentioned report asserts that effective preparation and management of supply chains may prevent contagion of a localized risk event: lack of sufficient preparation may amplify the disruptive impacts of events beyond the industrial sector into the societal domain. In particular, this is relevant in energy supply. Nevertheless, risks in long and complex supply chains are obscured by the sheer degree of coupling and interaction between sources, stakeholders and processes within and outside of the system; disruptions are inevitable, management and preparation are therefore difficult – in accordance with the Normal Accident Theory [33]. The WEF 2009 report upholds the warning: "Risk management must also account for interlinkages and remote possibilities. Low-probability, high-severity events, such as the terrorist attacks of 9/11, the Asia tsunami of 2004 and the global credit crisis do happen" [35].

Systemic risk in global infrastructure is emphasized in the 2010 report [36], page 23: "a major terrorist attack that closed a port such as Rotterdam, Hong Kong or Los Angeles for weeks would have severe economic consequences on world trade because it would inflict major disruptions in complex just-in-time supply chains that comprise the global economy". The conclusion from WEF is: "there is a need to balance the additional private costs to operate more safely that might negatively affect the firm's bottom line with the benefits of reduced global risks; that is the trade-off between private efficiency and public vulnerability."

Global supply chains are highly dependent on maritime transportation. Through reviews, little research has been found on the disruption vulnerability of Maritime Transportation Systems [MTS]. This hole in research is relevant to pursue further. The understanding of maritime supply chain disruption vulnerability may be better understood through using methods from fields where the understanding of such problems are more progressed – namely reliability and safety engineering. A core concept in my PhD work is to adapt the maritime safety-method Formal Safety Assessment [FSA] [37] into the domain of understanding maritime supply chain vulnerability.

A key question in this is whether to prevent a disruptive event from occurring or to prepare to respond to a disruptive event after it has occurred. At a glance, the question may seem trivial; it is better to not have anything happen rather than to deal with the consequences afterwards. However, given that there are almost endless possibilities for something going wrong; knowing which scenarios to prevent from is not a trivial task.

Secondly, not all risks can be foreseen or quantified; "unknown unknowns", or events one did not know one was vulnerable to, still may cause harm. Therefore, one should prepare to restore the ability of the system to perform its mission.

Thirdly, money is an issue: the cost-efficiency or "lean" trend of the latest 30 years [38], where organizations have minimized excess inventory and capabilities to cut cost, has made systems more vulnerable – one may fear that some cost cuts have reduced the damage tolerance of systems, such as illustrated by the World Economic Forum [34].

A two-tiered approach to addressing maritime supply chain vulnerabilities is suggested. Frequent and well-known risks, typically operational issues and recurring events from the past, can be foreseen. For these, the existing Formal Safety Assessment framework is adaptable with some adjustments. However, for low-frequency high-impact [LFHI] disruption scenarios, such as the Kobe earthquake, a consequence focused approach termed failure mode assessment is suggested.

Failure modes are about disregarding what hazards caused a disruptive event, and rather to understand the consequences such events have on the system. By looking at the maritime transportation system from a functional perspective, seeking what capabilities and functions are necessary for the system to be able to perform its mission, one may protect these functions without focusing on particular hazards and threats. Recognizing that there are endless numbers of hazards and threats, attempting to prepare the organization for all of these is fruitless. But there may be great value in preparing for the few ways that your system would fail. Through the grounded theory work of Rice [39, 40], and expansions to these by Berle et al [41], the authors argue to have captured the high level ways maritime transportation systems may fail. The essential question is then; which functions do you need to back up to make your supply chain work?

The basis for the six failure modes used in the failure mode research 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 [42]. The concept of failure modes is well known and used within safety and reliability application [43, 44].

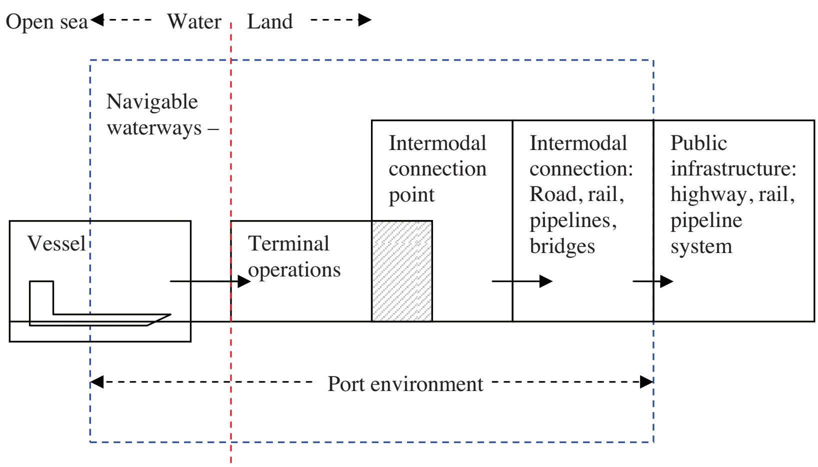
The U.S. Department of Transportation [45] defines the Maritime Transportation System [MTS] as composed of ports, intermodal connections, navigable waterways, vessels and users. We do not treat the user explicitly, as the interest of the user is covered by the definition of the mission of the transportation 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 papers one and two, 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 7; 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 7: Process of the maritime transportation system



When disruption occurs, reducing the consequences is the only possible action. In which ways can planning allow for restoring the ability to perform the mission of the system? The critical functions can be found in paper 1 in the attachments.

To ensure a comprehensive approach to understanding supply chain vulnerability, a framework for assessment of supply chains was deemed necessary. Instead of developing one from scratch, a concept was to adapt existing frameworks to the problem. Reliability engineering was found to be suitable, from which the methodologies had been used for numerous cases within risk management, offshore safety et cetera. The advantage of using tested methods includes that benefits and disadvantages are known.

Given that not all threats can be foreseen, nor can all threats be prevented from causing a disruption, supply chain disruptions are bound to occur. Reasons for this include that many disruptive events have a very low probability, although consequences can be large. The risk for each and every one of these is so low, and the number of potential threats so large, that preventing all events from occurring neither is feasible nor rational.

The concept of barriers may explain how to prevent hazards from leading to full blown disruptive events, as well as to reduce the consequences in case a disruptive event occurs. Hollnagel [46]. Barriers can be modelled as part of fault and event trees, which are discussed later in this dissertation.

The infrastructure needed to liquefy natural gas is very costly, the vessels likewise. To reduce capital and operational expenses, LNG supply chains are optimized to a high degree, leading to lean and tightly integrated systems with little slack. Societal dependence on natural gas is high, given that the most important usage area for natural gas is electricity generation. These properties; societal dependency and vulnerable maritime transportation networks where redundancy and buffers are expensive makes LNG transportation a relevant and timely subject for this research.

Humanitarian Logistics operations have been studied, to investigate if the insights from this research could be applied in this operational domain. Given time, cost and capacity constraints, maritime transportation may contribute in moving goods into a relief area and distributing goods to end users. Through using the developed frameworks to increasing the understanding of humanitarian relief logistics, this case also offers an example of possible implementation of the research.

1.4 Research context

This research project was funded by the Norwegian Research Council through the MARRISK research project. MARRISK was formed to answer the following research question [47]: “How should we able to engineer resilience into the maritime logistics chain that meets the vulnerability and risk taxonomies of the context, and finally be able to analyse and manage the vulnerability and risk scenarios in a proactive manner?”. The question of the author’s task in this project was to describe “in which ways the global shipping systems are vulnerable, and with our ability to analyse the consequences for global trading patterns and the shipping industry of these vulnerabilities, as well as the resilient measures within the shipping systems that are intended to cope with the vulnerabilities.”

In addition, for the author’s one-year research exchange at Massachusetts Institute of Technology, he was generously funded through the Fulbright Foundation, The Jansons’ fellowship and the DNV fellowship.

1.5 Research questions

Two research questions have been formulated for each of the four journal papers from which this dissertation is composed. The relation between the papers, supporting research and the contributions of this project can be seen in figure 8. Much of the insights on energy security and dependence on maritime transportation systems came from the initial research on LNG transportation, as described in TA1.

Paper 1: Failure modes in the maritime transportation system – a functional approach to throughput vulnerability
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?

Paper 2: Formal Vulnerability Assessment: A methodology for assessing and mitigating strategic vulnerabilities in maritime supply chains
RQ3: What would be a suitable framework for addressing maritime transportation system vulnerability to disruption risks?
RQ4: Which tools and methods are needed for increasing the ability of operators and dependents of maritime transportation to understand disruption risks, to withstand such risk, and to prepare to restore the functionality of the transportation system after a disruption has occurred?

Paper 3: The role of the maritime transportation system in relief supply chains
RQ5: How may maritime transportation systems contribute in humanitarian relief operations?
RQ6: What are the essential factors (critical capabilities) necessary for a maritime logistics operation within a humanitarian relief context?

Paper 4: Optimization, risk assessment and resilience in LNG transportation systems
RQ7: Can risk assessment methods combined with results from fleet planning provide more insight in creating resilience in maritime supply chains?
RQ8: Does the combination of risk assessment methods and deterministic optimization software provide adequate results for a supply chain planning problem under uncertainty?

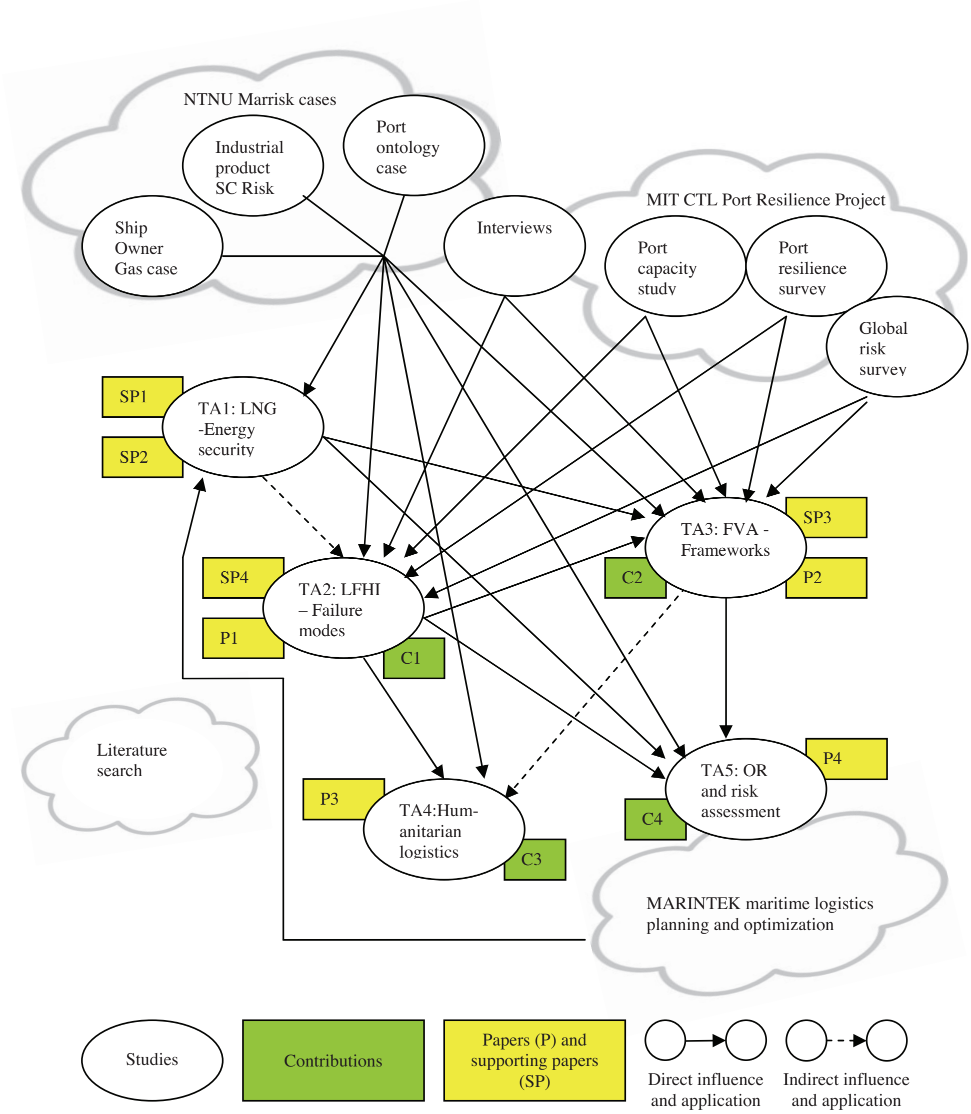
1.6 Research design

The research part of the doctoral fellowship period can be divided into five thematic areas:

TA1: Energy security, in particular for natural gas and global LNG transportation systems
TA2: Understanding of maritime transportation system failures, in particular for low-frequency high-impact scenarios,

TA3: Methods for systematically addressing how systems fail and how these may be made less vulnerable,
TA4: The relevance of maritime transportation systems in humanitarian relief operations, and how to strengthen these
TA5: The interaction between supply chain risk assessment and LNG transportation system optimization.

Figure 8: Studies, contributions and papers



As can be seen in figure 8, one study is associated to each thematic area. Three industry case studies were performed from the MARRISK project to understand practical aspects of supply chain vulnerability, insights from these were used in creating own frameworks and approaches in TA2 and TA3. A set of 20 interviews were performed, 16 of which as a part or the MIT CTL Port resilience project. In addition, support from three other studies not managed by the author was included, namely the MIT CTL port capacity study, the MIT CTL Port Resilience Survey and the MIT CTL Global Risk survey, the latter of which was only affiliated to the Port Resilience project.

1.7 Papers

1.7.1 Paper 1

BERLE, Ø., RICE JR, J.B., and ASBJØRNSLETT, B.E., *Failure modes in the maritime transportation system – a functional approach to throughput vulnerability*. Maritime Policy and Management, 2011. **38**(6): p. 605-632. [48]

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.

Relevance to the thesis:
This paper presents our findings in study 3, and serves as a continuation and expansion of the work done for SP4. It describes which key functions a maritime transportation systems is reliant on to provide its mission, and how one may create a more resilient transportation system through preparing to restore these functions. This paper belongs to TA1, corresponds to RQ1 and RQ2, presents C1 and lays the basis for C2, C3, RQ3 and RQ4, as well as to some extent RQ5 and RQ6. In short, this approach towards understanding low-frequency high-impact risk is one of the critical contributions from this thesis.

The independent contribution of the candidate:
I wrote this paper in its entirety, based on secondary paper 4. The approach was based on previous research at MIT, although the expansion into the maritime domain was a

novel approach. The concept was refined through discussions with Rice and Asbjørnslett. I took part in all interviews, except from four due to US Security rules and regulations. The questions for the 16 interviews done at MIT were developed in collaboration with Rice, the remainder by the author alone. The surveys were not my work, although I took part in the last stages of formulating questions for the MIT CTL Port Resilience Survey.

The contribution on James B Rice:
Rice managed the MIT CTL Port Resilience Survey, took initiative to and led the 16 interviews with terminal operators, port authorities and coast guard in the US and Panama. Further, he discussed the concepts and arguments with the author.

The contribution of Bjørn Egil Asbjørnslett:
Asbjørnslett supervised the paper, discussed the concepts and arguments with the author, and introduced the candidate to the problem.

1.7.2 Paper 2

BERLE, Ø., ASBJØRNSLETT, B.E., and RICE, J.B.J., *Formal Vulnerability Assessment: A methodology for assessing and mitigating strategic vulnerabilities in maritime supply chains*. Reliability Engineering & System Safety, 2011. **96**(6): p. 696-705. [49]

Abstract
World trade increasingly relies on longer, larger and more complex supply chains, where maritime transportation is a vital backbone of such operations. Long and complex supply chain systems are more prone to being vulnerable, though through reviews, no specific methods have been found to assess vulnerabilities of maritime transportation system. Most existing supply chain risk assessment frameworks require risks to be foreseen to be mitigated, rather than giving transportation systems the ability to cope with unforeseen threats and hazards. In assessing cost-efficiency, societal vulnerability versus industrial cost of measures should be included.

This conceptual paper presents a structured Formal Vulnerability Assessment [FVA] methodology, seeking to transfer the safety-oriented Formal Safety Assessment [FSA] framework into the domain of maritime supply chain vulnerability. To do so, two alterations are made: 1) The focus of the assessment is defined to be ensuring the ability of the transportation to serve as a throughput mechanism of goods, and to survive and recover from disruptive events. 2) To cope with low-frequency high-impact disruptive scenarios that were not necessarily foreseen, two parallel tracks of risk assessments need to be pursued: the cause-focused risk assessment as in the FSA, and a consequence-focused failure mode approach.

Relevance to the thesis:
This paper belongs within thematic areas TA1 and TA3, corresponds to RQ3 and RQ4, and results in contribution C2. It serves as a continuation of the work presented in SP3, and lays the foundation for the insights in TA5 in paper four. With the failure modes in

paper 1, this formalized approach provides a structured guideline in how to address maritime supply chain vulnerability.

The independent contribution of the candidate:
I wrote the entire paper, while concepts and arguments were developed together with and discussed with Asbjørnslett and Rice throughout the process. As for paper 1, I took part in all interviews, except from four due to US Security concerns. The questions for the 16 interviews done at MIT were developed in collaboration with Rice, the remainder by the author alone, under supervision by Asbjørnslett. The surveys were not my work, although I took part in the last stages of formulating questions for the MIT CTL Port Resilience Survey.

The contribution of Bjørn Egil Asbjørnslett:
Asbjørnslett proposed the concept to the first author, supervised the paper, developed and discussed the concepts and arguments with the first author. Further, he introduced the candidate to approaches for vulnerability assessments in a structured manner.

The contribution of James B. Rice:
Rice managed the MIT CTL Port Resilience Survey, took initiative to and led the 16 interviews with terminal operators, port authorities and coast guard in the US and Panama. Further, he discussed the concepts and arguments with the author.

1.7.3 Paper 3

BERLE, Ø., SPENS, K., and ASBJØRNSLETT, B.E., *The role of maritime transportation in humanitarian logistics*. Submitted to the International Journal of Ocean Systems Management, in review. [50]

Abstract
Humanitarian relief operations are characterized by limited transportation capacity at a high cost, in part due to high reliance on air freight, especially in the first days after a disaster has struck. This paper investigates critical supply chain capabilities needed to facilitate a transportation mode shift in humanitarian relief operations. Sea-transportation can both improve the capacity characteristics, as well as the agile characteristics of humanitarian relief logistics, the latter in particular through short sea distribution of goods to local areas of need. Sea-based transportation can increase capacity into a disaster area at lower cost, but requires an adequate sea-land interface. Also, with such capacities in place, short sea transportation can relieve road-transportation networks for moving goods to distribution centres, save from the final movement from distribution centers to end users. The approach provided is based on previous research using reliability engineering methods on supply chain risk management problems. An illustrative example is provided by means of data from the 2010 Haiti earthquake.

Key words: Humanitarian logistics, Supply chain capabilities, Haiti earthquake, Maritime transportation system

Relevance to the thesis:
This paper is particularly relevant for TA4 and corresponds to RQ5 and RQ6, and results in contribution C3. It serves as an illustration of the concepts in paper 1, applied to a practical case, as well as to illustrate the potential gains that are possible when maritime transportation is included in planning.

The independent contribution of the candidate:
This paper is the result of collaboration with Spens, with whom the author started to develop the idea at MIT. The introduction and background is a result of several iterations, where the writing has been shared about equal. The approach and conclusions (sections 3-5) were developed in collaboration with Asbjørnslett and written by the author under supervision by Asbjørnslett.

Karen Spens' contribution:
Spens initiated the paper, discussed the concepts and arguments with the author. She wrote about half of the introduction and background parts, focusing on the humanitarian logistics segments.

Bjørn Egil Asbjøprnslett's contribution:
Supervised the paper, with substantial input to concept development, and discussed the approaches and arguments with the author.

1.7.4 Paper 4

BERLE, Ø., NORSTAD, I., and ASBJØRNSLETT, B.E., *Optimization, risk assessment and resilience in LNG transportation systems*. Supply Chain Management: An International Journal, Submitted. [51]

Abstract
Purpose: This paper addresses how to systematically address vulnerability in a maritime transportation system using a Formal Vulnerability Assessment approach, create quantitative measures of disruption risk and test the effect of mitigating measures. These quantitative data are prerequisites for cost efficiency calculations, and may be obtained without requiring excessive resources.

Design/methodology/approach:
Supply chain simulation using heuristics-based planning tools offers an approach to quantify the impact of disruption scenarios and mitigating measures. This is used to enrich a risk-based approach to maritime supply chain vulnerability assessment. Monte Carlo simulation is used to simulate a stochastic nature of disruptions.

Findings:
The exemplary assessment of a maritime liquefied natural gas (LNG) transportation system illustrates the potential for providing quantitative data about the cost of disruptions and the effects of mitigating measures, which are foundations for more precise cost-efficiency estimates.

Research limitations/implications:
This simulation was done on a simplified version of a real transportation system. For resource reasons, several simplifications were made, both with regards to modeling the transportation system and with the implementation of the Formal Vulnerability Assessment framework. Nevertheless, we believe the paper serves to illustrate the approach and potential outcome.

Practical implications:
Practitioners are provided with an approach to get more precise quantitative data on disruption costs and cost/efficiency of mitigating measures, providing background data for decisions on investing in reduction of supply chain vulnerability.

Originality/value:
The combination of risk assessment methods and inventory routing simulation of maritime supply chain problems is a novelty. Quantifying vulnerability, effects of disruptions and effects of mitigating measures in maritime transportation systems contributes to a little-researched area.

Key words: Supply chain risk, maritime transportation, LNG, fleet routing and scheduling, Monte Carlo simulation.

Relevance to the thesis:
This paper is a continuation of the work done in previous papers, in particular P2 and SP1, and is relevant for TA5. The research questions which were investigated were RQ7 and RQ8, leading to contribution C4. The paper includes simulation and quantitative measures, which are lacking in the other papers, and provides a possible continuation to create a ready-to-use approach.

The independent contribution of the candidate:
The paper was written in its entirety by the author (except from the part about optimization tools). The concept was developed in collaboration with Asbjørnslett, the risk assessment and simulation approach by the author alone. Simulation model development was performed in collaboration with Norstad, who made the interface between the risk assessment and simulation tool. The author did all simulations, including setups, and performed data analysis on the results.

Inge Norstad's contribution:
Norstad developed the simulation model, programmed the risk assessment approach into the simulation model. He reviewed and discussed the results, and the presentation of the results.

Bjørn Egil Asbjørnslett's contribution:
Asbjørnslett supervised the paper, developed the concept in collaboration with the first author, and discussed the approach and arguments with the author.

1.8 Supporting papers:

SP1 BERLE, Ø. and ASBJØRNSLETT, B.E., Vulnerability in global natural gas supply chains: A qualitative assessment of disruption risks in LNG maritime logistics, in Logistics Research Network Annual Conference 2008. 2008: Liverpool, UK.

Relevance to the thesis: This paper served to give me an understanding of the world markets for liquefied natural gas, the major trade routes, and to lay the groundwork for later papers. Also, it involved a qualitative assessment on how trade routes are vulnerable in the ocean transportation leg.

My role: I wrote the paper in its entirety under supervision of Asbjørnslett, and presented it at the Logistics Research Network Annual Conference.

SP2 BERLE, Ø. and ASBJØRNSLETT, B.E., *Vulnerability in European natural gas supply chains*, in *SAMRISK*. 2008: Oslo.

Relevance to the thesis: This paper revolved around EU Europe's dependency on imported natural gas, both piped and in the form of LNG. It also served as an example of a sector characterized by high degrees of optimization and little buffers in the form of natural gas storage.

My role: I wrote the paper in its entirety under supervision of Asbjørnslett, and presented it at the Samrisk conference.

SP3 BERLE, Ø. and ASBJØRNSLETT, B.E., *Formal Vulnerability Assessment: A methodology for assessing and mitigating strategic vulnerabilities in maritime supply chains*, in Proceedings *of the European Safety and Reliability Conference*. 2009: Prague, Czech.

Relevance to the thesis: This paper was a preliminary version of the framework presented in paper two. It did not include the failure modes, and the LFHI risks were not clearly defined as a part of the problem. However, it did allow for presenting the adaptation of the Formal Safety Assessment framework to a wider audience of academics and practitioners.

My role: I wrote the entire paper under supervision by Asbjørnslett, and presented it at the ESREL 2009 conference.

SP4 BERLE, Ø., RICE JR, J.B., and ASBJØRNSLETT, B.E., *Failure modes in ports – a functional approach to throughput vulnerability*, in *ESREL*. 2010, Taylor&Francis: Rhodes, Greece. p. 190-197.

Relevance to the thesis: This paper represented the ongoing research on failure modes, which resulted in paper one. It allowed for the concepts to be presented to a wider audience, and to get feedback from academics and practitioners.

My role: I wrote the paper in its entirety under supervision of Asbjørnslett and Rice, and presented it at the ESREL 2010 conference.

1.9 Contributions

The scientific contributions of my thesis can be summed up in the four points below. These are discussed more thoroughly in section four.

C1: An overview of the critical functions necessary for a maritime transportation system's ability to move goods.

C2: A framework for systematically addressing vulnerabilities in maritime transportation systems, treating both operational and low-frequency high-impact risks, as well as incorporating cost/efficiency criteria in the assessment.

C3: The insight and understanding of failure and restoration of maritime transportation systems is applicable to humanitarian relief logistics, where the application of principles from commercial supply chain management is immature.

C4: Combining supply chain risk assessment with optimization tools for an LNG supply chain increases the robustness and resilience of the system and thereby the energy security of the recipients, while ensuring efficiency resource usage of the supply chain.

1.10 Thesis structure

Chapter 2: State of the Art
Within this chapter, state the art of current research within supply chain risk management, maritime supply chain management, risk management, humanitarian relief logistics and fleet scheduling is presented.

Chapter 3: Context and Research Design
The context, research design and progress of the research are discussed in this section.

Chapter 4: Results
This chapter contains the results from the empirical work and the contributions of the thesis.

Chapter 5: Evaluation and Discussion of Results
Results and methods are discussed in this section, included validity questions, limitations of the thesis and how the thesis relates to its context.

Chapter 6: Conclusion
Conclusions of the dissertation and suggestions for future work can be found here.

Appendix A: Four papers have been selected as essential in this research, and are enclosed in full.

Appendix B: Four papers are not included in the thesis as they do not contribute significantly to the value of the thesis beyond what is done by the papers in Appendix A.

Appendix C: The interview guide / questions for port & maritime transportation stakeholder interviews is enclosed.

Appendix D: The questions and text of the MIT CTL Port resilience survey is enclosed.

Appendix E: The survey used for the MIT CTL Global Risk survey is enclosed.

Appendix F: Co-author declaration

2. State of the art

"As if it were too great, too mighty for common virtues, the ocean has no compassion, no faith, no law, no memory." - Joseph Conrad, The Mirror of the Sea

In the following, state of the art of relevant literature will be presented. The literature is divided into supply chain risk management literature, maritime supply chains, humanitarian logistics and fleet scheduling. General supply management literature is only referred to through reviews in section 2.2.1.

The general topic of this thesis is risk and resilience in global maritime supply chains. Supply chain risk management is a fairly recent research subject, stemming back from around year 2000, see e.g. Asbjørnslett and Rausand [52], Svensson [53] and Norrmann [54]. Maritime supply chain risk management is similarly even newer, no comprehensive framework or discussion on the subject was found in reviews. However, literature exists for components of the maritime supply chain, such as liability in shipping, port operation et cetera, this is presented in section 2.2.2.

Humanitarian logistics set the context for paper three; a literature review of the field is therefore presented in section 2.2.3. Operations research methods are combined with risk assessment methods in paper four, a brief literature review of the relevant methods are therefore presented in section 2.2.4.

2.1 Definitions

Some essential definitions are provided below; readers are advised to consult the glossary in chapter 8 for more thorough definitions.

Risk may be defined according to industry standards, as: *a triplet of scenario, frequency and consequence of events that may contribute negatively* [55]. A hazard is *a source 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. [56]. 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 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 defined as: *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 [52].

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. [57]. Resilience is *the ability of the supply chain to handle a disruption without significant impact on the ability to serve the supply chain mission*. Resilience is about handling the consequences of a disruption, not about preventing a disruption from occurring. However, the effort to create a resilient system is made before a disruption occurs.

Failure modes are defined as *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, see Berle et al [41] for a comprehensive discussion.

2.2 Literature

2.2.1 Supply chain risk management

Recent comprenensive reviews of academic supply chain risk management papers include Rao and Goldsby [58], who present a typology of risks based on reviewed papers; Vanany et al [59], who sort papers based on types of risk and industry sector, and Tang, [60] who develops a framework to classify supply chain risk management literature into supply, demand, product, and information management. He also offers a review on quantitative methods in supply chain risk management. Kleindorfer and Saad [61] develop a conceptual framework for managing supply chain disruption risk, drawing out 10 steps in the process. Their key frame is that sources of risks need to be specified, assessed and mitigated. [62] Zsidisin et al. structures supply chain risk assessment techniques, in particular with an agency theory perspective: The key message is that business continuity planning methods may be used to manage supply risk.

Giunipero et al [63] present a review of 405 published journal papers on supply chain management (SCM) published until 2006 from nine journals, and structure these into 13 subject areas: 95 are about supply chain strategy; 74 on SCM frameworks, trends and challenges; 66 on alliances and relationships. Of five identified gaps in research, they identified the lack of research on global supply chains as one. The research of this thesis is related to the latter, as global maritime transportation systems is an enabler of global supply chains.

Greening and Rutherford [64] discuss disruptions in supply chain networks. Following a review, they state that there is a lack of literature on responding to supply chain disruptions, to which this research becomes relevant. Similar to what is argued in this thesis; the authors state that "much of the extant literature is focused on the mitigation of risk, implicitly assuming that sources of risk can be identified". 11 propositions are presented to illustrate how disruptions affect supply networks.

Tang and Musa [65] provides the most recent review of supply chain risk, structuring directions of research within the area between 1995 and 2009 through 138 journal papers. Their general perspective is that the research community has moved from vague descriptions of disruptions to managing supply chain risk in a structured system dynamics perspective. They provide six methods to advance the research in supply chain risk management.

Manuj and Mentzer [66] bring together concepts from logistics, supply chain management, strategy, operations and international management to propose a five step framework for comprehensive risk management and mitigation in global supply chains. This is comparable to the FSA method, except the fourth step, where Manuj and Mentzer do not solely consider cost/efficiency. Rather, they include factors such as complexity management and organizational learning in addition to performance metrics. The foundation for their risk assessment is identification of risk sources, similar to most reviewed frameworks. Manuj and Mentzer present seven risk management strategy categories: avoidance, postponement, speculation, hedging, control, sharing/transferring, and security, although they stress that these are closely related. The paper presents a thorough review of current literature on the matter. Risk assessment paradigms are presented as probabilistic choice versus risk assessment; namely reducing the average, allowing good to weigh up for bad, versus reducing the consequences for catastrophic events through minimizing regrets.

Craighead et al.[67] argue that supply chain disruptions are unavoidable. The severity of such disruptions depend on the number of entities (nodes) affected. To give a measure, they suggest that supply chain density, supply chain complexity, and node criticality may serve as explanatory variables for severity of a disruption to the supply network. Mitigation variables identified are recovery and warning capabilities. This is in line with Rice and Caniato [40] and Asbjørnslett [52].

Peck [68, 69] presents supply chain vulnerability through dividing the system into four layers: value stream and product, assets and infrastructure dependencies, organizations and inter-organizational networks, and the environment. She argues that given the inter-organizational nature of supply chains with many uncontrollable factors, we must accept complexity and limited managerial control. Furthermore, she argues that supply chain vulnerability is an organizational matter, not only related to functional supply chain management.

Juttner [70] gives evidence that supply chain stakeholders are worried about disruptions spreading across networks, what she terms “ripple effects”. Juttner, like many others, promote visibility in the supply chain, and report that a majority of surveyed industrial companies make efforts to increase visibility. However, they claim it is a problem beyond tier-one stakeholders. Juttners’ surveyed companies do make internal contingency plans in case of disruptions, but do not do so across the supply chain.

Hendricks and Singhal [71] investigated the stock price and equity risk effects of supply chain disruptions, and found that the abnormal stock return in the two years following disruption announcements were -40 %, the equity risk was 13.50 % higher in the year following the disruption than the year before. The reasons they point out are;
1) Increased complexity due to global sourcing, coordination needs between many parties, and long lead times; 2) Increased reliance on outsourcing and partnering, making ripple effects more likely; 3) Single sourcing strategies have increased the

vulnerability in case this supplier fails; 4) Focusing on reducing inventory, excess capacity and slack has coupled the various links, leaving little room for errors.

Wagner and Bode [72] support the results of Henricks and Singhal through a survey among executives of German companies, showing that supply chain characteristics such as a firm's dependence on certain customers and suppliers, the degree of single sourcing, or reliance on global supply sources are relevant for a firm's exposure to supply chain risk.

Risk assessment methods, such as Kleindorfer and Saad's, are in general focused in identifying sources. This is comparable to Manuj and Mentzers two risk assessment paradigms; whether to look at operational risks or to minimize the consequences of disruptive events. Pecks theory of supply chains being inherently vulnerable and prone for disruptions is an insight the author agrees with. The risk assessment paradigm, as presented by Manuj and Mentzer, combined with insight from business continuity planning, as suggested by Zsidisin et al., is in line with the message of this thesis: Risk assessments cannot prepare to mitigate all risks, and must therefore prepare to restore functions after disruptions occur.

Tang and Tomlin [73] sum up previous research on why risk reduction efforts are not widespread, although there is a wide acceptance of the existence of supply chain risk: 1) Firms do not know how to manage supply chain risks, and 2) Firms lack credible estimates of the cost of a disruption, obstructing a formal cost/benefit analysis to justify risk reduction benefits.

2.2.2 Maritime supply chains

A general overview and structuring of risk is presented by Drewry Shipping Consultants [74], where risk is structured into eight categories: Strategic, market, credit, financial, operational, legal, organizational and sovereign risk. This is the most comprehensive overview found by the author. Another notable Drewry report present issues and best practices of risk management in international transport and logistics [75].

The United Nations Conference on Trade and Development (UNCTAD) reviewed maritime supply chain security efforts in a report focusing on developing a structured framework of risk and vulnerability in maritime supply chains [76]. The focus of this research is security efforts; given the insights of this thesis regarding the mission centric approach, insights span wider. This report bring out many of the same efforts that have been pursued in this thesis, including using technical risk assessment methods on maritime supply chains and making cost/benefit assessments explicit.

UNCTAD brings forth a number of challenges with security risk assessments [76]:

- Insufficient knowledge of the complex processes that determine the probability and impact of the risk.
- Combination of low subjective probability, high uncertainty, and lack of consensus.
- Rarity of the occurrence of events, and thus little actuarial or historical figures.

- Unclear pattern regarding the value, allocation, transfer and distribution of costs and benefits among both participating and non-participating parties.

Supply chain risk assessments also have some significant problems, according to UNCTAD [76]:

- Different approaches to the scope, nature and flow configurations of maritime supply chain linkages.
- Limited understanding of the impact of a terrorist incident on a system's supply chain disruption and resilience capabilities.
- Inadequacy of the traditional approaches (probabilistic, actuarial, historical, etc.) to modeling security-risk threats and vulnerabilities, due mainly to the lack of historical data and the irrationality of the terrorist human behavior.
- Difficulty in quantifying and assigning costs/benefits across supply chain members with different exposure to risk.

Finally, UNCTAD present three "sources of risk" relevant for assessments of maritime supply chains [76]:

- Environmental: uncertainties arising from external sources such as terrorist or environmental risks
- Organizational: internal uncertainties arising within the supply chain such as strikes or production failures
- Network-related: referring to the uncertainties arising from the interactions between organizations in the supply chain

While the focus of the above mentioned UNCTAD report is coordination between nations and regulatory affairs, it has been seminal in laying the foundations for this research project. In the following, general literature on commercial supply chains is presented.

Panayides [77] discusses the relation between maritime transport, logistics and supply chains, in particular within the containerized cargo industry, and defines maritime transport as "transportation of goods between two sea-ports by sea". Logistics is "the function responsible for the flow of materials from suppliers into an organization, through operations within the organization and then out to customers", while supply chain management "involves the integration of all key business operations across the supply chain". In this he argues that logistics management is only a part of supply chain management.

Notteboom and Winkelmans [78] claim that the market environment in which ports operate has changed dramatically, and that the port (authority) must adopt new roles to cope with this change. Structural changes in markets include that organizations move from "economies of scale" to "economies of scope", relying on advanced production factors (know-how) and offering products with large variety and shorter life-cycles (hence, needing shorter time-to-market). This environment is offering new markets but with higher insecurity and risk. Supply chains increasingly are operated by flexible multi-firm networks that out-source large tasks, primarily in three forms: 1) Out-sourcing of the production of components, 2) Value-added logistics, where finalization of products is done near the customer, 3) Out-sourcing of transportation, warehousing and distribution through third-party logistics providers. Notteboom and Winkelmans suggest that port authorities take the lead in the development of port-related value added logistics activities, information systems and intermodality.

An example of ports and terminals adapting to this environment was found at a car-import terminal in the US, as a part of the interviews which are described (in part 4): The import terminal for cars consisted of a mass-customization plant for cars, having 100 car servicing stations with mechanics, able to perform modifications ranging from adding spoilers and sunroofs to changing faulty gear-boxes. One such operation had been to change over 20 000 gear-boxes for a manufacturer over a short time period, which is a complex and critical task.

Robinson [24] similarly argues that ports are elements in value-chain driven systems, and must be viewed as more than just a place performing complex functions in the chain. He argues the understanding of ports followed an evolution, moving from being understood as 1) places, 2) operating systems, 3) economic units, and 4) administrative units, into being 5) key elements “embedded in value-driven chain systems, in value chain constellations; they deliver value to shippers and other third party service providers in the value-driven chain; they will segment their customers in terms of a value proposition; and will capture value for themselves and for the chain in which they are embedded in so doing. Chain systems compete with chain systems.” In other words, the ports deliver value as a critical component of maritime transportation systems in which they take part, and for the supply chains dependent on these.

Song and Panayides [79] offers measures for port and terminal integration in the supply chain, and tests these measures empirically. Six parameters are identified as key for integration: 1) Use of technology for data sharing, 2) Relationship with shipping lines, 3) Value added services, 4) Transport mode integration, 5) Relationship with inland transport providers, 6) Channel integration practices and performance. The paper presents correlation between supply chain integration parameters and parameters of port competitiveness (such as cost, quality, reliability, responsiveness and customization) from an empirical survey, which is followed up in a later paper on sea-port integration [80].

Marlow and Paixão [81, 82] discuss the development of lean ports within the container segment, and offer discussions on agility and flexibility of these. They argue that 20 to 30 % of all transportation costs in chains are related to storage in ports, and that 80 % of port revenues come from 20 % of the activities. Costs incurred in ports are between 30 and 80 % of all waterborne transportation costs, depending on the presence of short-sea shipping. This gives grounds for actions to reduce waste, where Paixão and Marlow suggest a Business Process Redesign (BPR) framework. Through using Just-in-time and Lean-methodologies, they claim that there is significant potential for reducing waste. Freed capacities and increased insight into their own systems can then be used to give the port a competitive advantage through increased flexibility and agility in the systems.

Rodrigue and Notteboom [83] argue that sea-ports and terminals increasingly are taking an active role in value creation in supply chains through optimizing flows through the systems, such as by imposing berthing windows, dwell time charges and time slots for trucks. They argue container terminals are increasingly used as cheap temporary storage of consignments for shippers, rather than just as smooth facilitators between modes. Terminals can be seen both as bottlenecks and as warehouses, to illustrate the changing and increasing role of terminals in maritime supply chains, they introduce the expression “terminalization”, and investigate effects of the changing role throughout the maritime supply chains.

De Martino and Morvillo [22] investigate the interaction and interdependence between port stakeholders, as well as the change of ports from movement of cargo to value added logistics services. A part of this is to identify critical assets in the maritime supply chain, which is relevant, although the risk management perspective is not discussed. Li and Cullinane describe methods to reduce maritime liability risk, both for individual ship owners and for regulatory authorities [84]. Essentially, they argue that cost-benefit analysis is necessary for balancing the commercial interests of the ship-owners with the needs of society and other stakeholders doing business with these.

Little research exists on the overall maritime supply chain vulnerability. Carbone and De Martino [23] discuss the role of ports in supply chain management, with a practical case on Renault using the port of Le Havre, France. Their question is if and how port operators can face the challenge of higher supply chain integration. To understand this, they investigated four variables: 1) What kind of relationship exists between the port operators and the focal firm? 2) What services are supplied in order to satisfy customer requirements? 3) What information and communication technologies are used for the integration among the stakeholders? 4) Which key performance indicators (KPI) are shared by the actors of the supply chain? Through these, they are able to describe the relationships Renault has with its transportation suppliers.

Bichou, Bichou and Gray [85-87] argue that ports are an integrated part of supply chains, and that they should be treated as such. Further, they argue benchmarking is possible between ports and other intermodal connection points, and that this has an underutilized potential. As ports are parts of a larger supply chain, security measures should follow through; a conceptual framework is offered for this, relating the ISPS code to other security measures, and expanding the approach of the International Maritime Organization (IMO) to fit the extended supply chain security framework. Three challenges are given for port logistics and supply chain research: 1) The large number of firms involved. 2) The differences in functions and thereby strategic and operational viewpoints between a traditional port setting and a supply chain. 3) The large number of disciplines involved. They sum up that there is still much do be done in cultural integration between ports and supply chains.

Barnes and Oloruntoba [31] discuss the role of security in maritime supply chains, elaborating on various security initiatives such as the International Ship and Port Facility Security Code (ISPS), Container Security Initiative (CSI) and the Customs and Trade Partnership against Terrorism initiative (C-TPAT). Their argument is that the complexity of interactions between ports, maritime operations and supply chains create vulnerabilities that require analysis that extends beyond the structured requirements of these initiatives. They argue that there is a need to assess the goodness-of-fit of these initiatives, and suggest a new classification scheme for mapping vulnerability within ports and across supply networks. Essential steps in vulnerability management are 1) Crisis recognition, seeing warning signs, recognizing emerging disruptions and understanding how the supply chain will be affected, 2) Crisis management, where skills need to be developed before an accident occurs, and 3) Concomitant management strategies, such as developing partnerships with other stakeholders. Parts of this doctoral thesis are relevant to their suggestions for future research in proposing a framework for “identifying generic vulnerabilities in critical infrastructure at major ports”, evaluating the current status of port-based institution, and assessing low-frequency high-impact scenarios.

Kristiansen [88] gives a though introduction to safety and risk management within a maritime context. Ranging from general introductions to risk and uncertainty to statistical methods, risk analysis methods and management and operations frameworks, this is the most comprehensive work that the author has found on the subject within the maritime domain.

Harrald, Stephens and vanDorp [89] show that risk management methods can contribute to increasing the security of US sea ports, in particular against terrorist attacks, and argue that “any interventions that increase the security of ports must not only be effective, they must be economically sustainable”. Their perspective is that ports are complex systems composed of a set of loosely coupled economic systems, i.e. the port is a system of systems. For four shipping segments; Container, petrochemicals, bulk and ferry, they show an event chain in case of a disruption, the potential interventions, and the organizations responsible for these interventions

Ho [90] describes the Asia-Pacific Economic Cooperation (APEC) trade recovery program following a port disruption. A 2006 Booz Allen Hamilton study concluded that the economic impact on the 12 APEC economies as a result of a US port shutdown due to a terrorist attack would be significant, and increasing with the length of time that trade is disrupted. They cite that “if trade at the US port was impaired for 15 days, the cumulative loss of GDP for the 12 APEC economies for 3 years was estimated at US$82 billion dollars in 2006. The loss increases to US$175 billion for a 30-day impaired trade and to US$499 billion for a 60-day impaired trade.” This trade recovery program consists of three elements: 1) A plan of action for restoration to prevent unilateral and counterproductive actions, 2) A set of pre-established guidelines for re-establishment, and 3) A communications protocol to establish relationships and to enable information sharing. While this program is directed towards terrorism, the insights presented in this thesis indicates that this program should have a wider scope, including trade resumptions after disruptions like labor actions and natural disasters.

Yang [91] studies the impact of risk factors from the container security initiative (CSI) on the maritime supply chain in Taiwan, using risk assessment methods to understand the implications for the CSI and the 24-hour rule (US rule stating that contents of all containers bound for or transiting through the United States must be sent to US Authorities 24 hours before the container is loaded. One of the conclusions is that supply chain security measures are leading to an increase in logistics costs.

2.2.3 Reliability engineering

Learning from safety and reliability research, potential disruptive events may be categorized through the risk pyramid, see e.g. Bird and Germain [92]. 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

Rausand and Høyland [44] present the evolution of risk and reliability engineering from the 1930s onwards. First, the approaches were used to improve the quality of industrial products and to reduce air crash probabilities. A decade later, reliability engineering analyses were used for designing the V-1 missile. Failure mode assessments, as presented below, were first introduced in the 1950s. Space and missile research, including the Apollo program and development of intercontinental ballistic missiles led to further refining of the fields. In the 1970s, safety and reliability engineering was used for creating more safe nuclear reactors and for developing the Norwegian offshore industry. In the 1990s, Reliability engineering became an integrated part of product design.

Saleh et al [93] provide the most recent comprehensive review of concepts and developments within reliability engineering throughout the last decades. They argue that the development of reliability engineering has followed three idea tracks; the “organizational”, including theories such as man made disasters, normal accidents and the high reliability organization; the probabilistic risk assessment track, and finally the defence-in-depth and barrier approach track. The authors argue that these tracks have culminated into the systems engineering and control theoretic approach to safety from the 1990s onwards.

The essence of these is that the first track came with realizations that accidents follow a pattern and can be analyzed; that due to complexity and interactive coupling, accidents are bound to appear; and that organizations with proper training and preparations can prepare themselves to cope with uncertainty. The probabilistic track utilized analytical approaches, where a stochastic chain of events lead to a disruptive event. The third track is about defending the system against disruptive events and to minimize damage. Finally, the synthesis in systems engineering approaches is accentuating that system safety is a “control problem” needing a system theoretic approach. Interactions between components (not just single components), subsystems and stakeholders can lead to failures, and these must therefore be considered as such.

Seminal works in the reliability engineering domain include Turner’s “Man-made disasters” [94], Perrow’s theories on “Normal accidents”[33], Robert’s works on the high reliability organization [95], and the reactor safety study WASH-1400 report by Norman Rasmussen [96]. Systems engineering approaches are presented by e.g.

Blanchard and Fabrycky [97]. The most comprehensive work combining safety and systems engineering is Levesons “Engineering a safer world” [98], presenting why reliability and safety are not the same and that the interactions are what matters, as argued by Saleh et al. A summary of critiques of Quantitative Risk Assessment (QRA) approaches are presented by Apostolakis [99], which is relevant as approaches of this thesis are based on QRA approaches. Some of these works are discussed more thoroughly in section 5.

Aven and Kristensen [100] review the most common perspectives for understanding risk and uncertainty. The first partition they present in risk management is that of a positivist view – risk objectively exist and can be measured; and the Bayesian – where risk is a way of measuring uncertainty. Then, different paradigms of risk and uncertainty are presented: 1) The engineering approach using risk assessments, and looking to evaluate these using a cost benefit criteria. Quite often, risk assessments use predetermined risk acceptance criteria. 2) The economic decision-making perspectives, using utilities and rational decision making, often by assigning monetary values to all events. 3) The social science perspectives, considering people’s evaluation of and behaviour towards hazards. In essence, this is about subjective (individual) perception of risks and uncertainties. 4) The anthropological perspective, where clustered related convictions and perceptions of reality drive social responses towards risk. In essence, this is about a “group’s” perception of risk. Attempts towards unifying these above perspectives have been made by e.g. Renn and Klinke [101]. Aven and Kristensen [100] give their own perspectives on unifying the perspectives, demonstrating that such a unification is possible. Aven describes a structured and comprehensive approach in [102].

Vatn [103] give an overview holistic approaches to risk research in the offshore industry and how to systematically address this in a structured framework. Rausand et al.’s textbooks on risk management have given the author general insight into risk management [44, 104].

2.2.3.1 Relevant risk assessment methods

Some relevant risk assessment methods are presented below:

PHA

Preliminary hazard analysis (PHA) is an initial semi-quantitative analysis that is intended to identify all potential hazards and accidental events that may lead to an accident [44]. Other names include Rapid Risk Ranking and Hazard Identification (HAZID). The essence of the analysis is to break down the system into its components, and to identify all events that may lead to malfunction. This listing is often assisted by accident records and earlier analyses for similar systems, hazard checklists and standards, and expert judgment.

FMECA

The Failure Mode, Effect and Criticality Analysis (FMECA, sometimes also called FMEA) is a method to determine equipment functions, functional failure modes and possible causes and consequences of such failures [88]. In addition, fault detection and inherent provisions in the system design to compensate for failures are considered. The approach uses standardized forms, including elements such as function description of components, the elements mentioned above, as well as a ranking of frequency and severity, and a specification of reliability data.

HAZOP
The Hazard and Operability Studies (HAZOP) method is a detailed and comprehensive hazard identification method, often used in sectors such as process systems and software development [88]. The principle is to identify the components included in the system, define their purposes, and to analyze possible deviations from these. Normally, deviations are done through applying guide-words to processes, such as "too much" flow through a valve. HAZOP has been applied to supply chain problems by e.g. Adhitya et al. [105], who compare its use in supply chain to that of a chemical processing plant.

Fault- and event trees
Fault tree analysis (FTA) uses Boolean logic to graphically model logical relationships between equipment failures, human errors and external events that can combine to cause specific mishaps of interest, also called top events [88]. In qualitative measures, a fault tree singles out one "top event" at a time, the hazardous incident, and shows which basic events lead to such incidents. In quantitative measures, a fault tree should lead to what is defined as minimal cut sets. These are the minimal number of basic events that need to occur to result in an accidental event – a low number of events is naturally bad, as there are fewer barriers to an event occurring.

Event tree analysis (ETA) uses decision trees to model the possible outcomes of an initiating event capable of causing consequences of interest [88]. This modelling technique is very effective at modelling the effects of barriers and mitigation means after an accident has happened. In short, it assumes a chain of possible events, where each level of the chain involves two mutually exclusive outcomes.

Combining fault and event trees, and drawing this out creates what is called a bow-tie diagram. Drawing this out for all possible hazards creates a risk contribution tree. The risk contribution tree gives an overview of the entire system risk, including the direct contributing causes, the barriers which the system relies on, and the alternative levels of loss.

2.2.4 Humanitarian relief logistics

Humanitarian relief organizations have become prevalent after the second world war [106], including agencies such as the United Nations Childrens´ fund (UNICEF) and the World Food Programme (WFP), as well as a wide range of non-governmental organizations (NGOs) such as the Red Cross and Oxfam. Following a disaster, natural or man-made, delivery of aid is the cornerstone of the response of the humanitarian community. Logistics plays an important role in delivering this aid as it has been suggested that 60-80 % of the costs of NGOs are related to logistics. In monetary terms, an estimate is that the annual sum devoted to managing the humanitarian supply network exceeds USD 15 billion [107]. Up to half of logistics expenses occur before relief aid reaches those in need [108]. Reducing the NGO emergency aid costs with 20 % is realistic [109], freeing over USD 3 billion annually.

Although the significance of logistics in delivering aid has been recognized, the role of logistics and supply chain planning in humanitarian relief organizations has been argued to be limited. Relief organizations suffer from three shortages compared to corporate and for-profit supply chains [110]: 1) Lack of depth of knowledge: NGO leaders tend to be value-led 'activists', where few have corporate experience in supply chain management. NGOs also tend to lack support structures such as supply chain expertise, corporate relationships and infrastructure. 2) Funding biased towards short-term responses: NGOs tend to be financed by grants, paying time-bound direct projects, which are often short and chronically underfunded. This leaves little room, nor incentive, for investing in competence and supply chain improvement. 3) Lack of investment in technology and communication: Many NGOs do not have advanced IT and logistics systems, and may have undervalued its role in the overall efficiency of the operation, e.g. in procurement procedures.

While the majority of goods movement of practical and economical reasons has to be moved by sea, little relevant research has been found concerning the role of sea transportation and ports in humanitarian relief efforts, see e.g. Stephenson [111]. Due to capacity and cost reasons, beyond the initial response phase in the first few days of an intervention, a majority of goods and equipment can not be transported in by air. The need for a humanitarian relief operation, beyond the immediate response phase, is to be able to move large amounts of goods and equipment. This requires reliable transportation, flexible to handle the uncertainty of local conditions, the ability to prioritize between goods to maximize the utility given limited resources, and the ability to coordinate between a large number of stakeholders and NGOs, shippers, local authorities et cetera. Physical plans for the supply includes identifying suppliers, potential pre-positioning of stores, shippers, as well as potential staging zones and export or trans-loading ports.

Humanitarian relief can be defined as a "foreign intervention into a society with the intention of helping local citizens" [112]. Unfortunately, it is expected that these types of interventions will be needed even more in the future as the amount of natural disasters are increasing, in fact the amount recorded has multiplied more than sixfold over the last 30 years [113]. Relief supply chains (SC) also constitute a substantial industry that responds to over 500 disasters annually and result in loss of 75 000 lives and affect over 200 million people [114]. Academic research in humanitarian logistics prior to 2007 was mostly covered in practitioners' journals [115], however although still scarce, research in the field has recently received a lot of attention by logistic academics to the extent of the establishment of a new journal, the *Journal of Humanitarian Logistics and Supply Chain Management*.

There are few common denominators of HL research. Topics vary from performance measurement to customer service, facility location to vehicle routing, agility to the application of lean concepts. Oloruntoba and Gray investigate the applicability of supply chain agility on humanitarian relief logistics [106], by creating a supply chain that is lean and efficient on the supply side, while being agile and effective facing the end users. In light of a challenging funding environment, they argue that making donors understand that investment in routines and procedures necessary for longer-term supply chain efficiency and leanness – with low media impact, is a daunting task.

Van Wassenhove [116] elaborates on the complex context of humanitarian relief effort, in particular on the mechanisms that uphold the short-sighted and inefficient "firefighting mentality" of humanitarian logistics. In summary, a myriad of logistics concepts have been applied to the field – though research has largely followed practice and rarely set its agenda. An efficiency focus has also led to the frequent oversight of equity considerations in research.

Kovács and Spens present a framework for understanding humanitarian disaster relief logistics [115], distinguishing between actors, phases, and logistical processes, in addition to providing a solid literature review. Maon et al [117] highlight the potential for applying corporate insights into disaster relief, both through prevention and planning – as well as for the response and recovery phases. Parts of their contributions lie in that they provide a structured oversight over the elements and practices in disaster relief (table 1), an overview of challenges for disaster relief organizations (table 2), and examples of collaborations between corporations and relief organizations (table 3).

Research in the field is diverse, applying tools and techniques borrowed from other areas. Tatham and Pettit [107], however, argue that the contributions within humanitarian logistics can be characterized as considering the subject from a social, managerial or technological perspective; the implications of technical choices on the supply chain will be discussed later. Several articles that have appeared lately which describe the use of military concepts in the field of humanitarian logistics [118, 119]. Humanitarian relief efforts can adapt principles from commercial supply chain management as well as techniques and tools from other areas such as the military. This is what we have tried to capture in paper 3.

2.2.5 Optimization and planning

As shown in the introduction, maritime transportation is performed in three modes: 1) liner, 2) industrial, and 3) tramp shipping. Liner services primarily moves containers according to fixed itineraries and schedules, much like a bus. Industrial operators own and manage their own fleet, seeking to minimize costs. Tramp shipping follow cargos like taxis, focusing on profit maximization [120]. Fleet size and mix, as well as routing and scheduling of ships, is vital in securing the profits of stakeholders in the MTS. To achieve this, the usage of vessels must be optimized, see reviews by Ronen, [121, 122] and Christiansen et al. [123]. Optimizing over a chain, production capacity and storage must be included. Grønhaug and Christiansen describe a solution to an inventory routing problem for a LNG supply chain [124].

From the start, the operations research (OR) community worked with static and deterministic problems. This is relevant for many problems, and has contributed a great deal to resource utilization. However, the real world has considerable uncertainty associated with it. Also, if the problem is based on a real-life scenario, most likely new information and constraints will appear. If the model should still be relevant, it needs to be updated. In essence, types of OR problems can be divided along two axes: deterministic versus stochastic and static versus dynamic problems [125].

Given that a number of decisions have to be made in the presence of uncertainty, where ignoring this may lead to inferior or wrong decisions, it is important to include the modeling of uncertainty in transportation systems [126, 127]. One such way is stochastic optimization, where certain decision variables are unknown – this is a method that is still not fully implemented and in use in large scale commercial OR software. However, there is always a "trade-off between the realism of the optimization model [...], and the tractability of the problem", making it possible to solve [127]. Recent relevant literature on optimization of LNG shipping problems includes Andersson et al. [128], describing an inventory management problem of a vertically integrated LNG supply chain, and Rakke et al. [129], who present a heuristic for creating annual delivery programs with the presence of a spot market. The multi-start local search heuristic that is used for the scheduling software for the simulations in paper 4 are described by Brønmo et al [130]. In short, it bases itself on a large amount of starting points for the optimization, then uses local search to improve the solutions. To speed up the heuristics, only the best solutions are improved.

2.2.6 Conclusions from literature survey

Insights from the state of the art-chapter can be summed up as follows:

1) Supply chain risk management has been a field of growing interest the last decade, and has become fairly mature for land-based applications. Concepts and approaches can be adapted from this domain into the maritime field.

2) Maritime supply chains, the risks and vulnerabilities of these have not been extensively investigated in literature. In general, this was found to be a promising niche for research.

3) No structured framework for maritime supply chain risk management has been found. While general supply chain risk management frameworks, such as by Manuj and Mentzer [66], provide an overview of how to address risks. However, characteristics of the maritime transportation industry are not included, and the articles are, in the perspective of the author, too general to precisely contribute in addressing maritime supply chains.

4) Stakeholders in ports and maritime supply chains have a very operational perspective on supply chain vulnerability:
    a. Focusing on frequent events rather than the LFHI events.
    b. Focusing on prevention rather than response.

   In this, we argue that the focus of most reviewed literature has been "preventing incidents from happening". Some have discussed resilience as a business strategy, e.g. Sheffi [26], others have discussed planning to restore the systems through using business continuity management, e.g. Zsidisin [62]. However, to the extent of the reviews for this thesis, this subject has not been uncovered for maritime supply chains.

5) Maritime supply chain risk management is very directed towards security, i.e. that someone deliberately seeks to destroy the system, (rather than the functions-oriented perspective argued in paper 1). Typically, existing research within the maritime domain was focused on symmetric (state-on-state) or asymmetric (terrorist) war. However, following Rice and Caniato [40], the cause of disruptions is not always relevant for low-frequency high-impact scenarios; whether a port is destroyed by earthquake or bombing, it is still destroyed. For those dependent on it for cargo flows, the port can either be restored, or alternative routes must be identified.

6) No published research has been identified investigating the role of maritime transportation in humanitarian relief logistics. It is a field of growing focus, see e.g. [108]. The combination of an un-researched niche and the author's interest in restoration of transportation capacity left this a promising field.

7) The combination of reliability engineering methods and supply chain risk management problems has not been investigated. For technical systems, methods are tested and applied. However, technical systems are more tangible, where the interactions between components can be tested more easily compared to supply chains, in which large parts of dealings are taking place in what is essentially a social system.

8) Systems engineering perspectives to supply chain risk management can provide additional insight, by studying the interactions between components in a system, between systems and between stakeholders - this is in line with the trend sketched out by Saleh et al. [93].

9) Research on robust solutions to ship optimization problems under uncertainty are being developed. Optimization tools can provide insights into providing quantitative data for risk and vulnerability analyses of maritime supply chains.

3. Context and research design

"First there was the sky, high, pure and of a darker blue than he had ever seen. And then there was the sea, a lighter, immensely luminous blue that reflected blue into the air, the shadows and the sails; a sea that stretched away immeasurably when the surge raised the frigate high, showing an orderly array of great crests, each three furlongs from its predecessor, and all sweeping eastwards in an even, majestic procession."
- Patrick O'Brian, The Thirteen-Gun Salute

3.1 Context

As argued initially in this thesis, increasingly long and complex supply chains, in particular those reliant on shipping, are potentially vulnerable to disruptions. This is an aspect that NTNU wanted to address through the competence development project "Coping with Risks in Maritime Logistics – Managing risk, vulnerabilities and resilience in maritime logistics chains". This was funded by the Norwegian Research Council in collaboration with industrial partners such as Det Norske Veritas [DNV].

The task of my research project was to investigate models to contribute in such assessments; how to understand how these systems were vulnerable, the consequences of breakdown, and how to create systems with higher damage tolerance and/or the ability to restore themselves.

3.2 Delimitation

The contributions of this thesis are within the engineering economics domain. Primary focus areas for the research has been to produce insight into how maritime transportation systems can be vulnerable with regards to the ability to move goods, what possible causes and consequences may be, how to systematically approach the problem, how to mitigate problems, and how to create systems that are less vulnerable.

This thesis is not about health, safety and environment (HSE), although methods developed for this purpose are applied. Nor does it directly concern the financial side of disruptions. The thesis does not focus on sharing responsibilities between stakeholders, nor to discuss direct roles in planning to cope with and recovering from disruptions; only that such efforts should be collaborative.

Supply networks have not explicitly been included, although the general concepts should be applicable. For instance, figure 7 shows the elements of the maritime supply chain. However, there can be several systems competing in a marketplace. Also, within a single supply chain, relationships are not set in stone. On the short term, contracts may mitigate differences, on a longer term; collaboration may limit insularity between parties. Thereby, expecting a supply chain to act as one is an ideal state. Such discussions have not been a focus for this thesis.

3.3 Research design and progress:

The uncertain nature of a doctoral research project involves a number of iterations on theme, research questions, methods and results. Figure 8 in the introduction illustrated the overview of the thesis.

Yin [131] page 27 lists five components as vital for the research design:
1. Study questions: “who”, “what”, “where”, “how” and “why”-questions are relevant to describe what the purpose of the research is.
2. Study propositions: The testable questions, stated through a set of propositions.
3. Units of analysis: What sort of data defines a “case”, what is relevant information, and how do these relate to both the question at hand and previous research.
4. The logic linking the data to the propositions: the analytic techniques that compare the data with the propositions, such as statistical analysis of surveys.
5. The criteria for interpreting the findings: How certain can one be that the found results can be trusted, what are rival explanations for the findings? This is related to the question of validity.

3.3.1 Study questions

The initial task of the research project was to create understanding of what vulnerability in maritime transportation systems is. The first steps were coursework and initial studies to give the author an insight into the domain. Courses included systems engineering, risk assessment and risk modeling, in addition to fleet optimization courses.

Also, we set out to find practical cases for relating the research to the real world; a set goal for the research was that the insights should be applicable for practitioners. A plan was to collaborate with companies within LNG transportation to increase our understanding, thereby setting the stage for TA1 on LNG and energy security. Initial insights were reported in SP1 and SP2 on energy security, LNG shipping vulnerability and LNG import dependence.

Literature reviews and attempts to apply existing methods on realistic cases, as well as the shortcomings in particular in SP1 led the way for TA2 and TA3, the failure modes and the formal vulnerability assessment framework. The lacking pieces were the focus on LFHI risks and particular characteristics of the maritime transportation systems. In essence, the gap analysis in the existing research gave way for this research.

3.3.2 Study propositions

Research questions 1 - 4 captures the essential insights of the literature surveys, belonging to TA2 and TA3.The preliminary results of which were first communicated in SP4 and SP3, respectively, before final results were communicated in P1 and P2, leading to contributions C1 and C2.

Research questions 5 - 8 came from the author looking to apply the insight from P1 and P2 on practical problems, resulting in work done on TA4 and TA5. The results of which were communicated in P3 and P4, resulting in C3 and C4.

3.3.3 Units of analysis

The unit of analysis is the major entity that is analyzed in the study [132]. The general category is maritime supply chains (as seen in P1 and P2). Specific entities include the global LNG supply system (SP1 and SP2), three industrial supply chains (industy case 1-3), the US port system (MIT CTL Port Resilience Project), humanitarian supply chains exemplified by the 2010 humanitarian chains to Haiti (P3), and an exemplary LNG supply chain (P4).

3.3.4 Analytic techniques

As this study was looking into an area where little research had been done before, much effort was put into understanding what the state of the art was, to which extent the stakeholders considered and had knowledge about the problem, as well as to understand their approaches to supply chain risk management.

For this purpose, revealing stakeholders thoughts and ways of approaching the problem, Yin [131] suggests case studies, experiments, histories and analysis of historical data as methods for doing social science research. Case study methods are particularly recommended when "how" or" why" questions are being asked, and where the focus is on a contemporary phenomenon within a real-life context (p. 1).

A combination of quantitative and qualitative data was used for the assessment. The most useful insights from the surveys came from descriptive statistics such as basic ratios. The interviews however allowed for follow-up of the results.

The analytic technique used for the interviews is called "explanation building" by Yin [133] (p. 141). In short, we had a set of working assumptions, as well as the interview guide as can be found in appendix C. Starting with initial statements, these were compared with what the interviewed stakeholders responded. Through several iterations of the statements, we believe that we could have confidence in our understanding.

The last paper addresses how to systematically address vulnerability in a maritime transportation system using a Formal Vulnerability Assessment approach, create quantitative measures of disruption risk and test the effect of mitigating measures. These quantitative data are prerequisites for cost efficiency calculations, and may be obtained without requiring excessive resources. Supply chain simulation using heuristics-based planning tools offers an approach to quantify the impact of disruption scenarios and mitigating measures. This was used to enrich a risk-based approach to maritime supply chain vulnerability assessment. Monte Carlo simulation is used to simulate a stochastic nature of disruptions.

3.3.5 Criteria for interpreting findings

The validity discussions of this thesis can be found in section 5.

3.4 Research questions and methods

Paper 1: Failure modes in the maritime transportation system – a functional approach to throughput vulnerability
RQ1: How may one identify potential low-frequency high-risk disruption scenarios in maritime transportation systems?
RQ2: How does one reduce systemic vulnerability towards low-frequency high-risk disruption scenarios in maritime transportation systems?
The work on papers one and two went in parallel; where the insights of paper one were used to support the presented framework in the second paper.

The foundation of this paper came from the realization that surveyed literature implicitly assumed that all risks could be foreseen. Sheffi [26] illustrated that vulnerabilities could be prioritized based on the dimensions frequency and consequence (p. 31), and that there was significant value in planning to restore the systems. This was called business continuity planning by Zsidisin et al. [62]. 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 Rice and Caniato [40]. The concept of failure modes is well known and used within safety and reliability application [43, 44]. Through the grounded theory work of Rice [39, 40], and expansions to these by Berle et al [41], the authors argue to have captured the high level ways maritime transportation systems may fail. The essential question is then; which functions do you need to back up to make your supply chain work?

Challenges for this paper were in particular how to convey the message in a way so that the paper could be applicable beyond strict academic purposes. The solution chosen was a very example-rich form, where examples and cases were used to give the reader a perspective. For the same purpose (and for readability), the exact discussions on the selection of the failure modes were left out. Another challenge is how this process could be formalized for a practical example. Out suggestion is presented as paper 2, see below, where the failure mode approach towards supply chain disruption is done in parallel with a traditional methodology.

Limitations include in particular a discussion on who should perform the assessment. We have left this out, but our perspective is that this should be a shared effort between stakeholders. As much of the larger disruptions would imply stoppage throughout the supply chain, the responsibility for restoring transportation capacity should be equally shared. For another reason, there may be several ways to restore transportation capacity; one single stakeholder may not have access to all, leaving out more cost-efficient solutions.

Paper 2: Formal Vulnerability Assessment: A methodology for assessing and mitigating strategic vulnerabilities in maritime supply chains
RQ3: What would be a suitable framework for addressing maritime transportation system vulnerability to disruption risks?
RQ4: Which tools and methods are needed for increasing the ability of operators and dependents of maritime transportation to understand disruption risks, to withstand such risk, and to prepare to restore the functionality of the transportation system after a disruption has occurred?

The work in paper two implied surveying a number of possible existing supply chain, safety- and reliability frameworks, to determine what would be the most suitable solution for the problem at hand. As for existing supply chain approaches not covering LFHI scenarios, this became apparent through several processes; First, investigation of existing frameworks increasingly gave this conclusion. Also, the author read "The Black Swan" by Taleb [134], which was an inspiration, likewise was Sheffi's "The Resilient Enterprise" [26]. For a partner, the author took part in trying out doing a risk assessment for an industrial company's supply chain, starting with a structured hazard identification process. However, the author has not taken part in the continued research of this project.

The Resilient Enterprise, as well as a paper titled "Building a secure and resilient supply network" by Rice and Caniato [40] led the author to do a year as an exchange fellow at MIT. It was during this stay that the failure modes presented in paper 1 were refined. However, the work was started before this; an earlier version was presented at the ESREL 2009 conference in Prague, Czech.

The criteria for the vulnerability assessment were set based on previous literature, in particular Oehmen et al. [135] and Kontovas and Psaraftis [136] and interviews with stakeholders:

R1: The framework must be structured and systematic, with explicit declaration of responsibility for the framework and for updating it.
R2: The framework must support quantification of risks.
R3: The framework must anticipate risks and prepare for the unexpected.
R4: The framework must be explicit on cost/benefit assessments of risk; both the business and the economics side of risk management should be considered.
R5: The framework must be transparent.
R6: The framework should give room for future implementations of dynamic monitoring of vulnerability, e.g. risk influence modelling.

Formal safety assessment proved a good candidate for modification for two reasons; 1) it was simple, but complete. 2) It had been applied and tested previously, so the strengths and weaknesses were to a degree known. The question was then which steps were necessary to adapt the framework to a maritime supply chain context. The solution, using the failure modes, was found throughout my time at MIT. The work on papers 1 and 2 therefore progressed in parallel.

The questions remaining are how to actually use this, who should be responsible, and how could this be tested? As for paper 1, we believe this should be a collaborative effort throughout supply chain stakeholders. As the commercial operation depends on interaction between stakeholders, so should the risk- and disruption planning. For this research project, the full framework was not tested. However, an application of these was used in conjunction with paper three, to break down and understand the critical functions of a maritime component in humanitarian relief logistics.

Paper 3: The role of the maritime transportation system in relief supply chains
RQ5: How may maritime transportation systems contribute in humanitarian relief operations?
RQ6: What are the essential factors (critical capabilities) necessary for a maritime logistics operation within a humanitarian relief context?

The motivation for doing this paper came from a combination of events. As mentioned above, the author wanted to find a test case for the FVA and FM methodologies as described in papers one and two. The MIT Center for Transportation and Logistics had been doing research on humanitarian relief logistics. For this reason, Karen Spens spent a year at the center at the same time as the author.

Some practical questions arise: First, what exactly is a humanitarian relief operation? As defined in the paper, humanitarian relief is foreign intervention into a society with the intention of helping local citizens. Our focus was those relief operations formed as a response to natural disasters, requiring rapid build-up of resources, answering to scenarios with lack of oversight, as well as often being characterized by severe damages to infrastructure, requiring agility and flexibility.

What are the chokepoints and the largest constraints of this operation? We identified four factors that are relevant: capacity, time, cost and distribution. Capacity relates to how much goods you can move, the Haiti case proved that airports quickly get congested, limiting transportation capacity. The time to restore capacity is relevant; a sudden onset disaster scenario requires help to come fast. It has been suggested that 60-80 % of the costs of NGOs are related to logistics, by performing these tasks more efficiently, more help can be given for the same amount of scarce funds. The end distribution of the goods is important to consider –damaged and congested roads can lead to problems moving goods out from a central distribution node such as an airport.

The approach presented is intended both for large NGOs and organizations such as the United Nations World Food Program (WFP). The key takeaway is that planners should consider incorporating plans to use the maritime mode in humanitarian logistics, and that this may contribute to increasing transportation capacity for lower cost, with limited time loss. Combined with short-sea transportation, distribution may be facilitated.

Beyond discussions with practitioners within the maritime transportation industry and humanitarian logistics practitioners, as well as having some of these proof-read the paper for face validity, no practical attempts at testing this approach has been carried out.

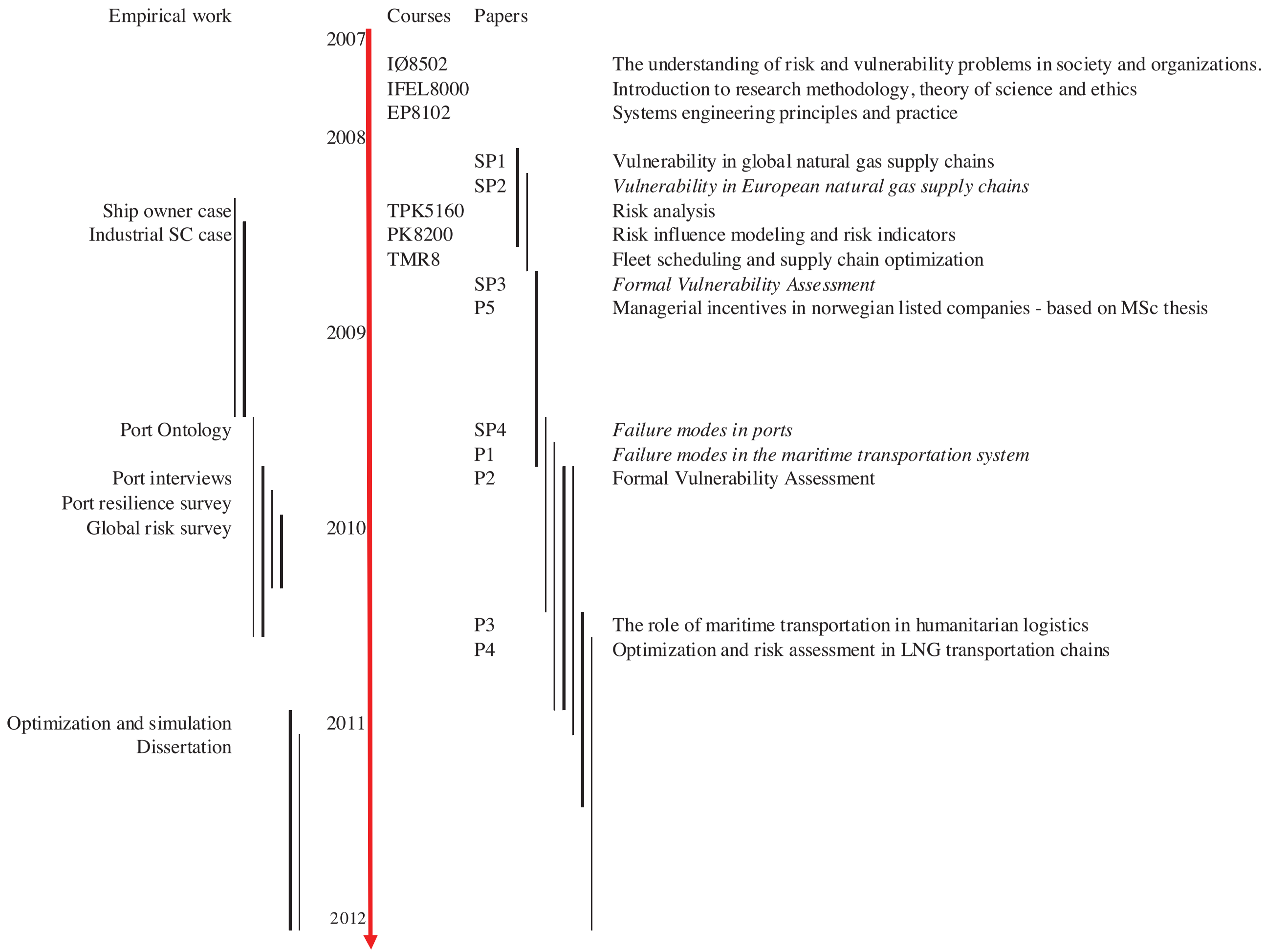
Paper 4: Optimization, risk assessment and resilience in LNG transportation systems
RQ7: Can risk assessment methods combined with results from fleet planning provide more insight in creating resilience in maritime supply chains?
RQ8: Does the combination of risk assessment methods and deterministic optimization software provide adequate results for a supply chain planning problem under uncertainty?

There are significant difficulties in coping with uncertainties in modelling maritime transportation systems. Stochastic optimization tools are still not mature, and no existing commercial approach has been found that solve a ship scheduling problems. Risk assessment methods combined with deterministic scheduling allows for including uncertainty about a supply chain scheduling, as well as to provide quantitative data of system reliability and its costs.

This paper addresses how to systematically address vulnerability in a maritime transportation system using a Formal Vulnerability Assessment approach, how to create quantitative measures of disruption risk and how to test the effect of mitigating measures. These quantitative data are prerequisites for cost efficiency calculations, and may be obtained without requiring excessive resources. Supply chain simulation using heuristics-based planning tools offers an approach to quantify the impact of disruption scenarios and mitigating measures. This is used to enrich a risk-based approach to maritime supply chain vulnerability assessment. Monte Carlo simulation is used to simulate a stochastic nature of disruptions.

In the paper, we argued that the combination of the Formal Vulnerability Assessment framework and using the commercial fleet planning tool TurboRouter with the Invent add-on to facilitate inventory routing, allows for enriching a vulnerability assessment of a transportation system. The Monte Carlo simulation combined with the inventory routing and scheduling tools illustrate how large impact combinations of disruption scenarios can do to a transportation system.

Figure 9: Timeline of the research



4. Results

"In the land of the blind, the one-eyed man is king" - Desiderius Erasmus Roterodamus

In the following, insights from the 20 interviews performed and the three industrial cases are presented, in addition to insights from two surveys; the MIT CTL Port Resilience Survey, and the MIT CTL Global Risk Survey. The author assisted in formulating the questions for the Port Resilience Survey and got direct access to the material. For the Global Risk Survey, the author got access to the material after the survey was completed, but did not in any way contribute to the results.

4.1 Interviews

In total, 20 interviews were performed to gain insight into the state of the art of supply chain risk management within commercial shipping operations. 16 of these were carried out as a part of the MIT CTL Port Resilience project. The author took part in all but four interviews, due to security clearance issues, such as with one U.S. Coast Guard Station. The final four were made by the author with four practitioners in Norway, all involved in the LNG transportation industry.

The 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, see appendix C for the questions form.

There were substantial difficulties in finding relevant interview cases, the selection of the 16 interviewees can be described as a convenience sample. To find interviewees, we reached out to a number of suitable stakeholders in relevant ports. In addition, introductions were obtained through previous relationships of James Rice, project manager of the MIT CTL Port Resilience Project, and through the interviewees.

Another relevant aspect was the "demographics" of the interviewees. To get a better grasp of the context, a wide spread of roles was desirable, to get a picture of a wide variety of roles in the MTS. To ensure to capture the efforts of the organization that the interviewee belonged to, we made sure that the subjects were "high enough" in the hierarchy, typically at managerial level.

The spread in roles, through not only interviewing the security managers, made us confident that we had achieved a solid understanding of the state of vulnerability management in the MTS, although we had the above mentioned convenience bias in selection of subjects. Given that in the final interviews, we gained little new insight, the search for more subjects was abandoned.

4.1.1 Insights from the interviews

Due to the explorative purpose of the research, the interviews were semi-structured in form. Questions asked revolved around investigating the subjects' perspectives on risk and vulnerability within both their own organization and in the global transportation system. The concept of resilience was another focal point: How did the companies prepare to restore the system, and what sort of flexibility was put into their transportation systems.

Examples of previous incidents were sought for. All interviewees could name at least one major maritime supply chain disruption, though most often not within their own organization. Through follow-up questions, we believe to have uncovered that most all respondents were very well aware of the risks of low-frequency high-impact scenarios, both that these occur and that transportation system downtime is very costly. However, respondents in general did not find that their organizations had specific plans or measures implemented to deal with this type of scenarios.

Discussions revolving around perceived vulnerability of maritime transportation systems in general tended to boil down to very security-related issues. This is understandable from the US operators' perspective, in particular given that both the government and academics have the same focus (in the aftermath of 9/11). However, as Rice and Caniato [42] argued through the supply chain security project, the consequences of security related issues such as terrorism are similar to the consequences of other causes, such as natural disasters.

Informants gave that overall, few systematic approaches to supply chain risk management were used. Reasons for this included lack of good frameworks, resources, complaints about own importance and access to personnel: "we are a too small player to devote significant resources to this".

A large operator provided an overview of their terminal risk management process. We did not get access to any background documentations around the workings of this, though through interviews it seemed the purpose was to provide a checklist of potential security hazards of the terminal. In particular, access control and anti-terrorism efforts were key factors in the hazard list we were shown. However, through follow-up questions, the risk management process seemed to be the result of a previous effort; no-one were responsible for updating the hazard list, and no process for systematic subsequent surveys existed.

Respondents in general replied that little could be learnt from benchmarking other organizations, coming from the attitude of finding themselves unique. A catch-phrase that was expressed frequently was that "if you have seen one port, you have seen one port". Causal factors leading respondents to giving this statement can range from 1) Actual lack of comparability between ports, 2) Lack of oversight between different ports and the operation of these, 3) Lack of willingness to realize similarities between ports, 4) Lack of willingness to learn from other organizations / to benchmark operations to best-practices. The author would argue that 2-4 are likely causation factors, although this was not pursued further. 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, leading to the argument that benchmarking between transportation systems, and thereby creating taxonomies of vulnerabilities in the MTS is feasible.

As we increasingly came to the conclusion that little new insight was gained from the interviews, the search for more respondents was aborted.

4.2 Industry cases

Three industrial cases were completed as a part of the PhD work within the MARRISK project, in addition to a number of preliminary meetings that did not result in specific cases. The goal was not clearly defined before starting, focusing more on explorative discussions on the context and challenges of the industry, perceptions on risk et cetera. Due to confidentiality clauses, the nature of the cases and the partners cannot be described in detail.

4.2.1 Ship owner

The partner is a large international shipping company that owns and operates a fleet of vessels within its segment. Results from the cases was more insight into how the sector is operated from the practitioners side, how practitioners think about risk and resilience, and how they adapt to such a setting. The main contributions of this case were increased insight in how essential explicit cost/efficiency estimations are for practitioners, the limits of resources available for such assessment, the "acceptance level" for theoretical concepts (i.e. that frameworks and tools should be hands on and applicable), and that our (at the time) initial ideas of focusing on LFHI risks were well founded.

4.2.2 Industrial supply chain

– advanced technical product with a global customer base.
The case was to identify potential risks and vulnerabilities for the spare parts warehousing and distribution for an advanced technical product. Due to the high cost of spare parts, the number of parts involved and the global distribution of customers, the client wanted to reduce global supply chain costs. However, the customers depended on high availability of the product, introducing significant constraints in the possibilities of removing warehouses.

Examples of companies that are advanced in such methodologies include Caterpillar Inc., which cut costs by implementing flexible "virtual warehouses", basically allowing for Caterpillar to buy back unused parts from its customers warehouses and redistributing these where needed [26] (p 229).

The research done around this project enforced the same insights as in the Ship Owner Case. In addition, it gave the author more insight into the workings of a global supply chain operator, the design of which, and practitioner's perspectives on the tasks as hand.

4.2.3 Port ontology

The project was partially run by a partner company, where the goal was to develop an ontology for the port as a hub between maritime and land based transportation. This is in line with the resilience project of Mansouri et al. [137]. To start with the obvious question; An ontology can be described as by Howe [138] as:
1. (philosophy) A systematic account of Existence.
2. (artificial intelligence) An explicit formal specification of how to represent the objects, concepts and other entities that are assumed to exist in some area of interest and the relationships that hold among them.
3. (information science) The hierarchical structuring of knowledge about things by subcategorising them according to their essential (or at least relevant and/or cognitive) qualities.

In short, the project sought out to create a model to describe the workings of a port by defining a "universe of discourse", in which a set of agents could communicate about the domain without operating on a shared theory – or allowing people from a wide set of fields to collaborate in a discussion on the port. This could be achieved by defining a set of representational terms, where definitions associate the names of entities in the universe of discourse (e.g. classes, relations, functions or other objects) with human-readable text describing what the names mean, and where formal axioms constrain the interpretation and use of these terms [138].

Our potential insight was that we could contribute in
1. Enriching the ontology to make it cover elements that make it suitable as a basis for quantitative risk and vulnerability analyses.
2. Further study into the technology mapping sequence, where the ontology could contribute to a simulation model of the system.

In particular the consequence side was deemed to be relevant, following the research done on LFHI risks. The areas studied by the author included accident scenarios based on:
- Blast effects (i.e. the propagation of a negative consequence throughout the system).
- Emerging effects – i.e. observing when gradually increases of workload on a port/terminal system would result in that the system as such or some of its bottlenecks 'would choke', with considerable reduction in throughput as a direct consequence.

However, due to significant difficulties combining a very detailed and advanced theoretical approach with my focus on practitioners left us to not continue the collaboration on this project.

4.3 Surveys

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.

For the MIT CTL Port Resilience project, a survey was made with stakeholders in the port domain, including shippers, port authorities and terminal operators - the questionnaires can be found in appendix D. A total 525 respondents provided insight into disruptions in the port environment [139]. The largest group of respondents was shippers (n=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 Port Resilience Survey was that, although not conclusive, highly focused entities may not have a full view of the system. This is in line with what we experienced in these interviews. 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 7, 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 us insight in thoughts on vulnerability mitigation and failure modes among supply chain stakeholders - the questionnaires can be found in appendix E. Three pieces of information were particularly relevant for the FM approach: 54 % of 1,350 valid respondents would spend more or much more on planning and implementing risk prevention measures, 30 % 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.

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. Labor 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.

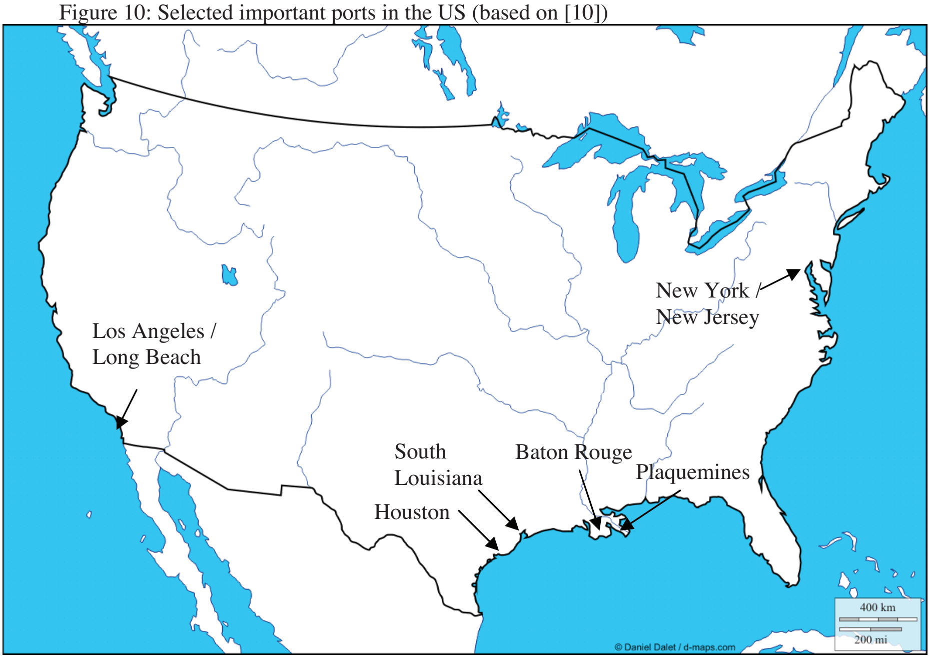
4.4 Port Capacity Study

The Port Capacity study was focused on understanding where there major cargo flow in the US went. Its principal contractor was the US Department of Homeland Security, having realized that no-one actually knew the US port capacity for a set of goods. The model based itself on using the cargo volumes shipped in 2007 for all US ports, sorted by 10 commodity categories ranging from container to food and farm products. For each of these the model removed one port after another to study its total impact on the overall commodity category carrying capacity [140].

The results from the port capacity study showed that surprisingly few ports stood for the majority of goods movement. For all goods types except manufactured goods and raw materials, less than 20 ports handled 80 % of the volumes [140].

In particular food and farm products and chemicals were relevant in the US setting. The top three ports handled respectively 45% and 40% of total volumes [140]. Given that a single of the most important ports would fail, over 25% additional port capacity would be needed to absorb the volumes. It is also relevant that all six ports were located in the Mexico Gulf area (Food and farm products top 3 Ports: South Louisiana, New Orleans, Plaquemines. Chemicals top 3 ports: Houston, South Louisiana, Baton Rouge). Some ports stand out in being top 3 most important in several categories; South Louisiana with six of the ten categories, New York / New Jersey with five, and Los Angeles / Long Beach with four. This illustrates that the US relies on a very limited set of ports for the majority of its exports and imports.

Figure 10: Selected important ports in the US (based on [10])



The contribution of this study was that it provided a quantitative measure of the US dependence on a limited set of vital ports, the loss of any of which would significantly reduce the overall transportation capacity of the US port system. Limitations exist in the model, in the data material behind the model and in the methodology chosen.

4.5 Methods that have not been explored fully: possible continuation

Scenario planning is a tool that has not been pursued in this thesis. Kroneberg in his thesis on innovation in shipping by using scenarios [141] defines these as "structurally different stories about how the future might develop". To use this methodology, he presents a set of necessary and sufficient conditions (p 10) including that the future is uncertain, and presents three requirements; 1) The number of scenarios should be between two and five, 2) the time horizon of the scenarios should correspond to that of the strategic decisions to be made, 3) scenarios should embrace the extremes of the future. In other words, scenarios describe a limited set of extreme future scenarios, to which the organization in question may choose to adapt. Scenario planning methods could possibly be adapted to help generate failure modes and weak points of the assessment.

Simulation methods could have given insight into how disruptions spread in transportation systems and how mitigating factors could respond to such events. As mentioned initially, large supply chains are complex with interconnected parts, where the connection and influence between the elements of the system are not necessarily readily apparent. The use of simulation based on heuristics-based optimization tools as done in paper 4 is a simplified version of this.

Practical cases with industry stakeholders where the presented approaches could be tested and adapted to a real-life case could be a promising route. Such case methods were used for understanding the state of the art, but could be used more extensively to add value in weeding out flaws of the approach.

4.6 Contributions from the research.

4.6.1 Contribution 1

An overview of the critical functions necessary for a maritime transportation system's ability to move goods.

Corresponding to paper 1: Failure modes in the maritime transportation system – a functional approach to throughput vulnerability
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?

One of the essential insights throughout this doctoral research was that most existing research, as well as the focus of practitioners, was on preventing events from occurring, rather than to plan to restore systems after a disruption has occurred. The insight was that planning for LFHI events can be done by focusing on the system's mission rather than the system itself. The loss of the ability to perform certain tasks or functions will limit or remove the ability of the system to perform its mission, i.e. move goods. In particular, through identifying these functions, preparing to restore these, the system has a greater ability to recover from low-frequency high-impact risks.

4.6.2 Contribution 2

A framework for systematically addressing vulnerabilities in maritime transportation systems, treating both operational and low-frequency high-impact risks, as well as incorporating cost/efficiency criteria in the assessment.

Corresponding to paper 2: Formal Vulnerability Assessment: A methodology for assessing and mitigating strategic vulnerabilities in maritime supply chains
RQ3: What would be a suitable framework for addressing maritime transportation system vulnerability to disruption risks?
RQ4: Which tools and methods are needed for increasing the ability of operators and dependents of maritime transportation to understand disruption risks, to withstand such risk, and to prepare to restore the functionality of the transportation system after a disruption has occurred?

Reviewed literature showed that no comprehensive framework existed to assess the supply chain vulnerability in maritime transportation systems. Also, most existing supply chain research focused on preventing events from occurring. A number of possible approaches were examined, mainly from reliability and safety engineering. Most of these existing methods were used within maritime, offshore and nuclear safety assessments. In the end, the Formal Safety Assessment was found to be a satisfactory candidate, being comprehensive, flexible enough to be applied to a setting, straight-forward, and explicitly including cost/efficiency evaluations.

The drawbacks of the existing FSA framework was that it was focused solely on technical risk, that an implicit assumption was that threats could be foreseen, thereby aiming for removing sources of risk as long as this was cost-effective. Therefore, the insights shown in paper 1 were included, specifically introducing treatment of low-frequency high-impact risks in addition to the aforementioned "foreseeable" risks.

4.6.3 Contribution 3

The insight and understanding of failure and restoration of maritime transportation systems is applicable to humanitarian relief logistics, where the application of principles from commercial supply chain management is immature.

Corresponding to paper 3: The role of the maritime transportation system in relief supply chains
RQ5: How may maritime transportation systems contribute in humanitarian relief operations?

RQ6: What are the essential factors (critical capabilities) necessary for a maritime logistics operation within a humanitarian relief context?

The research done for paper 1 and 2 provided an overview of the maritime transportation system and the risks within this. Initially, it came as a surprise that existing academic research did not fully recognize the value of maritime transportation in relief logistics.

Parts of the research went into understanding what the bottlenecks in a relief operation are. Our focus became the ability to move large amounts of goods swiftly into an area following a sudden onset disaster, and to distribute the goods to where these were needed. In particular, the three weeks needed to restore maritime transportation chains following the 2010 Haiti earthquake was surprising, given the significant cargo carrying capacity and cost advantage of the MTS compared to air transportation.

4.6.4 Contribution 4

Combining supply chain risk assessment with optimization tools for an LNG supply chain increases the robustness and resilience of the system and thereby the energy security of the recipients, while ensuring efficiency resource usage of the supply chain.

Corresponding to paper 4: Optimization, risk assessment and resilience in LNG transportation systems
RQ7: Can risk assessment methods combined with results from fleet planning provide more insight in creating resilience in maritime supply chains?
RQ8: Does the combination of risk assessment methods and deterministic optimization software provide adequate results for a supply chain planning problem under uncertainty?

Optimization tools allows for structured analysis of complex problems, where mathematical formulation of problems allow for maximizing utilization of limited resources. Recent advances in algorithms and heuristics allow for design and operation of complex and more efficient global supply chains, exploiting synergies across geographic locations, supply chain functions and time.

In particular, optimization tools for practical problems are typically designed to operate in a deterministic setting, assuming that the world is predictable, and that variability is limited. However, there is a growing focus on low-frequency high-impact scenarios. These are the scenarios that very seldom occur, but when they do, they create large problems for the supply chain. The large number of such possible scenarios makes the total possible impact significant; although little can be done to prevent all these events from occurring. Extreme examples are the 1994 Kobe earthquake and the 2002 Los Angeles dock lockout, both with massive consequences to business and infrastructure. Neither of these are encompassed in the sort of problems where operations research [OR] methods are normally applied.

This paper addresses the gap between optimizing a transportation system based on mathematical models and supply chain risk assessment of these systems. In essence; can risk assessment methods be used to improve the handling of uncertainty in decision planning in large and complex supply chains?

To model a real life scenario, a stochastic model allows for investigating complex systems and including rare scenarios. Monte Carlo simulations introduce random numbers into a model. By repeating the analysis a large number of times, the properties of the system become evident. This paper uses risk assessment methods to determine what may go wrong in a maritime supply chain, and how to cope with disruptions. To determine the effects of disruptions and mitigating measures, Monte Carlo methods and operations research tools are used to quantify effects.

The purpose of the approach presented is not to give the final answer to how risk analysis and mathematical planning tools can be integrated. Rather, this is intended as a conceptual paper to present this novel approach. We argue that the combination of the Formal Vulnerability Assessment framework and using the commercial fleet planning tool TurboRouter with the Invent add-on to facilitate inventory routing, allows for enriching a vulnerability assessment of a transportation system.

5. Evaluation and discussion of results

"The only true knowledge is knowledge of one's own ignorance" - Socrates

At the start of this research project, my questions revolved around questions such as what is a transportation system failure. How can we understand transportation systems in this context? How are transportation systems vulnerable? How do people think about vulnerability? How can we systematically address vulnerability, and what is it we are really trying to protect?

To start with the first; a central definition that laid the foundation for much of the later efforts was what we termed the "mission centric approach", in essence that the goal was to protect the mission of the transportation system. The mission was defined as the ability of the transportation system to move goods. Separating the ability of the system from the physical properties (the nuts and bolts) of the system laid the groundwork for the failure mode assessment, where a limited set of functions or capabilities had to be protected.

"The Black Swan: The Impact of the Highly Improbable" by Taleb [134] was, for all his flaws, an eye opener for the author in how to approach risk and uncertainty. Taking it back to Socrates, Taleb quotes him on that "the only true knowledge is knowledge of one's own ignorance". Taleb further bases his argument on Francis Bacon, stating that among the greatest of human fallacies is that of assuming more order than what actually exists in a chaotic nature. Taleb's behavioral argument is that people are wired for narratives, not statistical uncertainties. Also, he argues people tend to expect past events to repeat, rather than preparing for those events that actually matter; those that are rare and unpredictable. His term for these are "Black Swans", named after the positive certainty that existed in Europe until 1697 that all swans are white. In this thesis, such events have been termed low-frequency high-impact scenarios (LFHIs), accentuating that we care about those that may impact the system's ability to perform its mission.

Combining the insights in the paragraphs above, an argument on coping with supply chain vulnerability can be formed: Given that we know the draw towards preparing for the past, and that we believe that the most important events are those we do not foresee, systems need to be able to cope with unforeseen events. In other words, transportation systems need not only have the ability to resist disruptive events, they should also have the ability to restore themselves once a disruption occurs.

In this line, the cost-efficiency argument is relevant. To which extent should transportation systems have the ability to withstand threats, and how fast should transport capacity be restored, given that a cost is incurred to give the systems such abilities? There is also a cost to having time delays in restoration. Sheffi [26] argues that there in essence are two strategies to coping with disruptions; robustness and flexibility. Robustness is the ability to withstand threats, flexibility is the ability to reconfigure system resources in possession to restore and uphold the ability to perform the mission. His argument is that both are needed. However, the balance and cost/efficiency trade-off is not trivial. Tang [60] sums the lack of efforts up as no-one gets credit for an event that did not occur.

A foundation for doing credible cost-efficiency tradeoffs is the ability to quantify risk. Given that risk can be defined as a combination of scenario, probability and consequence, in particular the latter are relevant to put numbers to.

However, quantifying risk is notoriously hard to do, due to a set of reasons: First, supply chain risk management does not allow for experimenting in the closed confines of a laboratory. This sets the potential for experiments apart from for instance risk assessments in technical systems, where a mechanical part can be stressed over time under observation. Second; transportation systems are characterized by complex and interactions between the components. Combined with high and increasing interaction between components, as argued by Perrow [33], is a recipe for breakdown. Third, the number of potential threats that may cause a disruption is immense. Combining this with limited oversight of the interactions and complexities of the transportation systems leaves putting exact numbers to the scenarios at hand at best as difficult.

The solution generally used when trying to assess a scenario characterized by one or more of the three factors above, is simplification; the easiest of which is “expert judgment”. In essence, someone with above average insight into the problem make their best guesses on what the occurrence rate or possible consequence of a disruption would be – a version is to average the numbers found by several experts. Such assessments can be helped by structured techniques, but in essence they are subjective. On the other side, “in the land of the blind, the one-eyed man is king”: an estimate may be better than no information, as long as it does not lead one into a false sense of knowledge.

Examples of organizations that are engineered to have very low occurrence rates of disruption, termed high reliability organizations [HROs], include aircraft carriers and nuclear power plans [142]. These are made in response to theorists such as Perrow [33], who in the Normal Accident Theory stated that accidents are inevitable and are bound to occur. Weick et al [142] (p 37) argues that high reliability comes from the capability to discover and manage unexpected events. This again comes from mindfulness of the situation, which originates from five factors; Preoccupation with failure, reluctance to simplify interpretations, sensitivity to operations, commitment to resilience and underspecification of structures. In essence, the approach is that of being incessantly searching for failures rather than focusing on success. The relevant argument is therefore; how much of the lessons from HROs can be included in a supply chain before the costs are too high, both through extra measures, and through reduced focus on profits? There are no easy answers to this.

The author subscribes to the insights presented by Saleh et al. [93], stating that system safety is a “control problem” needing a system theoretic approach. Interactions between components (not just single components), subsystems and stakeholders can lead to failures, and these must therefore be considered as such. This is also the essence of the failure modes as presented in papers 1 and 2; the interactions between the components of the maritime transportation system, as well as the functions within these components is fundamental to understanding how a transportation system can fail and how to prepare to cope with such failure.

As described in paper 4 and section 4.6.4, we argue that understanding vulnerability and the effects of mitigating measures in complex systems is difficult. We argue that the combination of the Formal Vulnerability Assessment framework described in paper 2, and using Monte Carlo simulation and a fleet planning tool allows for quantifying vulnerabilities and the effects of mitigating measures in a transportation system, as done in paper 4. The ability to provide quantitative data allows for pricing vulnerability. Our approach is focusing on maximizing cargo moved.

5.1 Practical implications of the research:

The primary takeaways from this research can be summed up as follows:

1) Organizations should accept that not all threats can be foreseen, nor can all of these be prevented from causing a disruption to the transportation system. This is in line with the Black Swan Theory, as described earlier [134].

2) Likewise, organizations should accept that disruptions are bound to occur, in line with the Normal accident theory [33].

3) Organizations should plan to restore the most critical functions, as described in paper 1 and 2. To cope with this, the organization first should describe the supply chain on which it is dependent. What are the flows in the system? Which of these flows are the most critical; i.e. without which the operations would have to shut down immediately, the cost incurred of shutdown would be large etc. Are there any nodes in which a single component of ability breakdown will cause significant damage to the system? This is generally referred to as a single point of error, and is detrimental to the reliability of the system.

4) Supply chain stakeholders get a structured breakdown of the maritime transportation system as described in paper 1. This is describing for the entire system. However, a single stakeholder probably will not achieve large results by themselves, as measures to increase the overall ability of the transportation system would incorporate several stakeholders throughout the chain. The structured breakdown is a starting point for further discussions, also at a more detailed level. Supply chain stakeholders are presented with a framework on how to address the issue of supply chain vulnerability.

5) The potential in using the MTS for both transportation of goods into a humanitarian relief area and using short sea shipping for final distribution is illustrated.

Humanitarian relief operations are as illustrated in paper 3 dependent on moving large amounts of goods into areas often characterized by damaged infrastructure. Over-reliance on air freight limits capacity and makes organizations incur high logistics costs. Preparing to use and to restore maritime transportation in humanitarian relief can increase transportation capacity and reduce transportation cost.

The last-mile distribution problem is relevant in a disaster context, due to the above mentioned risk of damaged infrastructure. As airports and the distribution of goods out from these may become bottlenecks in the immediate response phase of an operation, short sea shipping should be included as an alternative transport corridor in planning of spreading out and distributing of goods. This could be understood as an extended 'last mile logistics' problem, as described by Balcik et al. [143].

6) Vulnerabilities in a maritime transportation may be better understood using a Formal Vulnerability Assessment approach in combination with tools to create quantitative measures of disruption risk and test the effect of mitigating measures. These quantitative data are prerequisites for cost efficiency calculations, and may be obtained without requiring excessive resources. In our approach, we have simulated an LNG supply chain using heuristics-based planning tools. Monte Carlo simulation is used to simulate a stochastic nature of disruptions. The exemplary assessment of a maritime liquefied natural gas (LNG) transportation system illustrates the potential for providing quantitative data about the cost of disruptions and the effects of mitigating measures, which are foundations for more precise cost-efficiency estimates.

5.2 Limitations of the thesis

Limitations of this thesis touch several dimensions. In the scope, both the limited time available for doing a research project and the lack of initial structure in the work limit what is possible to achieve. The latter is relevant for both the process itself and the knowledge gained and created. The author would argue that any research process is an iterative one, not linear and stepwise – a certain maturity through iterations is therefore necessary to properly understand the subject, the limits of existing research and the potential and limits of one's own work.

Given that the field was not well described in theory, the majority of the work done has been in the qualitative domain. This descriptive approach serves well to illustrate the maritime transportation systems, the problems of vulnerability and the possible approaches to mitigating this. However, ideally, the research should have had a more quantitative focus, providing numbers that could be tested.

Also, while the research has given a solid theoretical foundation for risk assessment, it is not necessarily ready to use for practitioners. One question is who should be responsible for this assessment, to take the lead in effectuating and implementing the assessment and the conclusions of this – which has not been discussed thoroughly. The difficulties in finding industrial partners may have contributed to less off an industry perspective in the research than what would be ideal.

This research spans over several fields, ranging from maritime economics, supply chain management, risk analysis, to logistics and fleet optimization. It is not feasible to be an expert in all fields, nor has it been a goal. Ideally, the research could encompass an even broader theoretical foundation, including methods such as scenario assessments and simulations.

Practical problems include the difficulty of finding relevant cases and collaborators. The fact that not much industrial collaboration has led to anything beyond discussions and interviews has been a constraint to the research.

An issue that has not been thoroughly discussed is the relation between vulnerability in ocean transit and in the port environment. The failure mode methodology does not include the ocean transit as somewhere to focus, although recent events continuously remind us that this is a source of vulnerability in maritime transportation systems. For instance, piracy has become a source of worry the latest decade [144]. Somali pirates operating in the Indian Ocean have taken control of a number of vessels the last five years (source): In 2010, 49 ships were successfully hijacked off the horn of Africa [145], currently. At the time of writing, 23 merchant ships are being held, with a total of 510 crew members being hostages [146].

Two more issues that have not been thoroughly investigated is firstly the diverging objectives of stakeholders and capacities to bear risk, and secondly how to properly account for and compensate for such disparities. Such differences are also relevant between "private" supply chain operators and "the public" in form of society dependent on the supply chain. This type of issue has been briefly described in this thesis and by other academics. One way to approach this is to consider differences in risk bearing ability by using insurance measures, although this has not been pursued thoroughly in this thesis.

Practical implementation of the suggestion of this thesis has not been attempted. This is related to the lack of deep collaboration with industry stakeholders. However, to the extent possible, the research has been made with an industrial perspective in mind, to create applicable knowledge for industry stakeholders.

5.3 Evaluation of research questions

The research questions were formulated as a part of the research leading to the individual papers. As the research was an iterative process, insights gained throughout gaining understanding of the problems forces the research questions to be reformulated to be more precise. Ideally, the process should be to formulate the final questions before commencing the project; this was not realistic for this research process. The author firmly believes that the overall contribution was reinforced by the iterations done to the research questions. In the end, the research questions precisely describe the questions asked and answered, such as RQ1: "How may one identify potential low-frequency high-impact scenarios in maritime transportation systems?".

The state of the art identified a set of gaps in existing research. While filling the gaps in existing research was an infeasible task for this PhD project, the research questions (RQ) set out to contribute in that direction.

5.4 Evaluation of Contributions

The contributions correspond to the research questions of the respective papers as indicated in section 4.6.

Contribution 1 provides a structured approach towards coping with low frequency high impact disruption scenarios in maritime transportation systems. This is a novel approach, both by setting out to solve a problem not previously described, and through the structuring of the problem by describing the critical functions and capabilities.

Contribution 2 provides a structured framework for a comprehensive vulnerability assessment by combining the insights around low-frequency high-impact scenarios with the safety-oriented formal safety assessment framework. For safety issues, the FSA is widely applied and accepted. Given this and the potential of the failure mode approach, the FVA seems promising. However, the method has not been applied in practice, leaving this a negative issue.

Contribution 3 similar to the above contributions provides a structured approach, and answers to the lack of existing research on the role of maritime transportation in humanitarian logistics.

Contribution 4 mitigates one flaw of this research project, namely the lack of quantification. Also, it adds to general research by bridging reliability engineering methods and mathematical optimization within a maritime supply chain risk management context.

5.5 Evaluation of Validity Threats

Validity can be defined as “the best available approximation to the truth of a given proposition, inference, or conclusion”, as by Trochim [132]. In essence, there is a chain of circumstances: 1) is there a relationship between what is argued as cause and effect (conclusion validity)? 2) Is this relationship causal (internal validity)? 3) In this general within the construct (construct validity)? 4) Is this general to other places, times and people (external validity)?

5.5.1 Conclusion Validity:

Conclusion validity is the degree to which conclusions we reach about relationships in our data are reasonable. [132]

On the developed methodologies:
Insights and feedback from discussions with practitioners, as well as our own attempts to falsify these by seeing if challenging scenarios would fit into our frameworks lead us to argue that the conclusion validity of the methodologies is acceptable.

On the cases:
Insights from the industrial cases provided practical insights and proofing that the initial thoughts and approaches could be valid for practitioners. Insights from these and the MIT CTL surveys were triangulated by interviews to ensure that we had a consistent picture of the understandings and thoughts on supply chain disruptions and risks. Follow-up questions in the interviews allowed us to investigate whether the lack of supply chain risk assessments was an actual case or a lack of reporting. Also, consistent throughout interviews was that no-one systematically prepared for LFHI incidents. This leaves us to believe that we have credibly explored and revealed the state of the art in the maritime transportation industry.

On the insights provided:
Failure modes:
The failure modes have been presented at an academic conference (ESREL 2010), and have been discussed with academics and industry stakeholders. Also, the authors have through a number of iterations tried to find flaws in the argumentation and the structuring of the maritime transportation system. One effect of this assessment was that demand failure was not anymore considered a property of the system. Rather, the failure to respond to changes in demand was considered to be the supply chain property, as this was a factor that could be influenced in the system design.

Formal Vulnerability Assessment:
The framework was first presented at an academic conference (ESREL 2009), and has been discussed with academics and practitioners. In addition to this, the FVA being based on an existing and tested safety and reliability framework after reviews of possible candidates, the authors are confident that the framework will provide insight in practical implementations. Possible improvements and further credibility may come from real-life realizations.

Humanitarian logistics
The functions of the humanitarian logistics' system rely on the research done for paper one and two, as well as through exploring literature from previous humanitarian, military and civilian supply chains. In addition, practitioners were used for face validity of the paper. We believe that our insights contribute to a better understanding of the problem, although cases involving more stakeholders in the industry could better validate such results.

Optimization and risk assessment:
System parameters were chosen so that the configuration to a large extent should represent an existing system. Given that the model and the optimization of this were done in a realistic, albeit simplified manner, the results are credible in our opinion.

5.5.2 Internal Validity:

"Assuming that there is a relationship in this study, is the relationship a **causal** one?" [132]

The majority of the tasks in this research were exploration of the current state of the art, and to create structures to better understand and analyze transportation systems.

The key questions for the surveys are whether our conclusions could be deduced from the data material, or if there were alternative explanations for the answers. The triangulation of data through follow-ups in the interviews allowed for some insights. However, we did not interview respondents directly on their answers (e.g. “in question 5.1, why did you answer …?”), but rather through explorative questions (e.g. “How does your organization build in resilience?”). We do believe that we were able to enrich the data with the follow-up, thereby strengthening our confidence in the material.

A problem for the internal validity of this thesis is that by design, it was “non-experimental” [132], i.e. that there was no control group or similar – we only surveyed stakeholders in the industry, where there was a strong selection bias (as mentioned earlier).

5.5.3 Construct Validity:

“Assuming that there is a causal relationship in this study, can we claim that the program reflected well our **construct** of the program and that our measure reflected well our idea of the **construct** of the measure?” [132]

Did we actually measure the parameters that we sought out to investigate? Or in other words, were our methods well suited for the problem at hand?

The port resilience survey set out to map the current rate of disruptions as experienced by industry stakeholders. Respondents gave that most disruptions are minor, although some major events do occur – just as expected. We saw that the respondents informed us mainly of disruptions within the parts of their value chain where they worked, not a surprising result neither. This survey basically confirmed what we believed from before.

Theories such as that stakeholders lack oversight were deduced from the lack of responses about other parts of the value chain – this could not be confirmed from the survey. However, as we did interviews, we could follow up on leads, strengthening our belief that this theory in fact could be relevant. Interviews with a limited number of stakeholders cannot statistically confirm such a statement, leaving us concluding that for this purpose, it was not well designed. The general perspective was that we got insight into what we looked for, and that the method was suited.

5.5.4 External Validity:

“Assuming that there is a causal relationship in this study between the constructs of the cause and the effect, can we **generalize** this effect to other persons, places or times?” [132]

Our study revealed that there is little understanding of low-frequency high-impact scenarios in the maritime transportation industry. Hence, little efforts are made to protect the system against these, as we suggest through preparing to restore a limited set of essential functions. A general insight that may apply wider is that such planning may be limited.

In essence, our interviews confirmed that Taleb's description of understanding of risk (being fooled by assuming history would repeat itself and by oversimplification and expecting order in a chaotic system) was prevalent also in the maritime industry. We believe that although the major part of the empirical research was done in a US context, the insights can be generalized to the maritime transportation industry in general. We also think that results can be applied outside of the maritime domain, although then in parallel to similar research.

The combination of risk assessment methodologies, simulation and operations research methods is promising, where little existing research has been found. This approach may be extended beyond the maritime supply chain risk management domain.

5.6 Reflections on the research context

This research has been performed as a result of "research push", rather than "industry pull". In this, the author with associates and supervisors has identified that maritime supply chain risk management is an important field, that supply chains are in fact vulnerable towards disruptions, and that there currently is not a large focus towards mitigating this problem.

Naturally, no ready made solution could be presented to industry stakeholders throughout the process of searching for potential industry partners. A number of fruitless, or at least not fertile enough, discussions with representatives have not led into a continued closer collaboration. Generally, they were "looking for something more ready-to-use" or more "hands-on". On the other side, these have, like the interviewees, expressed that the research is timely and relevant.

The wish of the author is that, while the research is theoretical and untested, it may contribute to better understandings of maritime supply chain vulnerability in the future. Also, given that the approach has been drawn out through the papers, a more applicable framework is ready for future research.

Research is not done "in a vacuum". At the very general level, the author belongs to a Western modern cultural setting, with a market-based perspective on allocation of limited resources. It is not given that all assumptions, arguments, reflections and conclusions would be identical if the author had a different cultural perspective. On the more specific side, the thesis belongs to a subject rooted in the intersection between engineering and economy subjects. A social scientist may argue that systems as presented are more about the interactions between people, and less about nuts and bolts. This has certainly been a factor in structuring the approach. At the methodological level, the choice of methods, using selected reliability engineering methods on a supply chain problem has provided certain insights and contributions. Would similar results have been obtained using other methods, and what would be different? And would other research partners have given other insights? To conclude, the author firmly believes there is no single best approach to address the questions asked in this thesis. All that remains is having confidence in that the thoroughness and methods chosen has provided a solid result for both practitioners and academics.

6. Conclusion

‘*Plans are nothing; planning is everything*’ – Dwight D. Eisenhower
‘We are what we repeatedly do” – Aristoteles

World trade increasingly relies on longer, larger and more complex supply chains, where maritime transportation is a vital backbone of such operations. The “mission centric approach” is the essence of this thesis, focusing on transportation systems ability to move goods. Numerous and complex interactions between parts, combined with strong focus on lowering costs by removing buffers create systems that are more prone to being vulnerable. In particular, this is visible in the LNG transportation industry. Very high infrastructure outlays needed provides incentives for lowering costs by removing buffers; combined with high societal dependence on LNG imports for purposes such as electricity generation create vulnerabilities.

This research has contributed in creating a structured approach for understanding how maritime transportation systems can break down, what possible consequences may result from such breakdowns, how organizations may approach such problems in a structured manner, and how supply chains may be given the ability to restore themselves after a disruption has occurred. In particular, this is relevant for low-frequency high-impact scenarios, given that while the individual probability of occurrence for these is low, the almost endless number of possible disastrous failures lead to a combined high probability. Real-life observation confirms this impression; Black swans, thousand-year waves and catastrophic failures of systems do happen.

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.

The proposed formal vulnerability framework sets out to create a platform for a systematic, structured and transparent overview of a specific defined maritime transportation system. Through a thorough structuring of the current status of the system, a joint platform for a shared understanding between the stakeholders can be made. Then in turn, using both the hazard- and the mission focus for addressing the vulnerabilities of the system, a wide spectrum of potential disruptive events has been covered. This approach is novel compared to reviewed supply chain risk assessment frameworks.

In essence, the sea-side of a humanitarian maritime transportation system does not differ from commercial transportation systems. However, on the port – and hinterland side, a set of challenges occur. Our approach seeks to use a concept for reducing the vulnerability of commercial sea transportation systems on a humanitarian relief problem. Through planning to restore the critical functions of the MTS, larger amounts of goods may be moved into a relief area at a lower cost, contributing to both higher efficiency and effectiveness. Short sea shipping should be included as an alternative transport corridor in planning of spreading out and distributing of goods.

Risk assessment methods combined with deterministic scheduling allows for including uncertainty about a supply chain scheduling, as well as to provide quantitative data of system reliability and its costs. We have provided a conceptual approach for testing the sensitivity of an LNG transportation system to disruptions. In this, the cost of introducing mitigating measures can be compared to the potential benefits these offer. Essentially, a foundation for a cost-benefit assessment is thereby provided.

The essence of this thesis is that interactions between the components of the maritime transportation system, as well as the functions within these components is fundamental to understanding how a transportation system can fail and how to prepare to cope with such failure.

6.1 Contributions

The following are the essential output of this research:
C1: An overview of the critical functions necessary for a maritime transportation system's ability to move goods.

C2: A framework for systematically addressing vulnerabilities in maritime transportation systems, treating both operational and low-frequency high-impact risks, as well as incorporating cost/efficiency criteria in the assessment.

C3: The insight and understanding of failure and restoration of maritime transportation systems is applicable to humanitarian relief logistics, where the application of principles from commercial supply chain management is immature.

C4: Combining supply chain risk assessment with optimization tools for an LNG supply chain increases the robustness and resilience of the system and thereby the energy security of the recipients, while ensuring efficiency resource usage of the supply chain.

6.2 Future work

This thesis has been limited to the engineering economics domain and the ability to move goods. As mentioned in the delimitations in section 3.1, this thesis is not about health, safety and environment, although methods developed for this purpose are applied. Nor does it directly concern the financial side of disruptions. The thesis does not focus on sharing responsibilities between stakeholders, nor to discuss direct roles in planning to cope with and recovering from disruptions; only that such efforts should be collaborative. All of these are rich potentials for future research.

Societal dependence on maritime transportation systems is the condition that this thesis relies on. The author sees interactions between single companies, supply chain networks of multiple companies and society dependent on this as a promising field of future research. What are the wants and incentives of these "levels of stakeholders", and how may clarification of these roles provide a situation where all stakeholders are better off?

One of the future works is that a publishing company, based on paper 2, invited the authors to write or edit a full book based on the subject. Possible expansions of this research are numerous, and would include further discussions on the intersection between a number of fields, including supply chain management, supply chain risk & resilience, and reliability engineering, where the latter is a primary source of knowledge for the former in the context of supply chain management. One way to approach this book would be to reach out to selected researchers to write about relevant subjects. We would need to know what exactly the organization is looking for with regards to extent and theme. Our approach could be based on the issue of risk, reliability and vulnerability of transport systems as such, with a specific focus on maritime transport and logistics systems in examples and applications.

Practical implementations of the ideas could be relevant for both direct tasks and more indirect effects, and may provide benefits both for research communities and for practitioners. By direct, we mean contributing to increasing the understanding of how supply chains may break down, and how to reduce such vulnerability. Indirect may be for stakeholders in supporting industry, such as maritime insurance companies looking to expand their product portfolios by offering insurance for a wider scope of risks in the maritime supply chain.

6.3 Concluding remarks

Supply chain risk management is a subject to which significant research interest has been devoted in the last decade. As this thesis has shown, limited efforts have so far been devoted to the maritime side of global supply chains, although seaborne trades are indispensable for a number of commodities and goods flows. Hopefully, this thesis and the papers may contribute to new insights, both for academics and practitioners.

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8. Glossary

Accidental event - event or chain of events that may cause loss of life, or damage to health, the environment or assets [147]

Agile - Agility is a business-wide capability that embraces organizational structures, information systems, logistics processes and, in particular, mindsets. A key characteristic of an agile organization is flexibility [148].

Barrier - Hollnagel [46] describes the concept of barriers as an obstacle, an obstruction or a hindrance that may either: 1) Prevent an event from taking place, or 2) thwart or lessen the impact of the consequences after an incident has happened. Hollnagel divides the types of barriers into four: physical, functional, symbolic and incorporeal (immaterial) barriers.

Damage tolerance – essentially robustness, the ability to withstand a threat from resulting in an accidental event

Defense in depth – Flemming and Silady provides three definitions for the term:
1. (direct) A set of well defined design features in an installation (nuclear power plant) that provide multiple and physical lines of defense between the hazard and the public
2. (process defense-in-depth) Incorporates defense-in-depth thinking into the licensing requirements. These requirements include the single failure criterion, safety margins reflected in various acceptance criteria, special treatment requirements, and the General Design Criteria.
3. (scenario defense-in-depth) This type of defense-in-depth reflects the PRA (probabilistic risk assessment) perspective of safety philosophy in which all conceivable combinations of initiating events and successes and failures of plant safety features are considered in the definition of scenarios

Effectiveness – Effectiveness is the extent to which goals are accomplished [149].

Efficiency – Efficiency is a measure of how well resources expended are utilized [149].

Failure modes - Failure modes are defined as *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, see Berle et al [41] for a comprehensive discussion.

Framework – Frameworks can be defined as [150]
1. A structure for supporting or enclosing something else, especially a skeletal support used as the basis for something being constructed.
2. An external work platform; a scaffold.
3. A fundamental structure, as for a written work.
4. A set of assumptions, concepts, values, and practices that constitutes a way of viewing reality.

Flexibility – see robustness and flexibility

Hazard - A hazard is *a source of potential damage* [55].

Lean - Lean is about doing more with less [148]. The term is often used in connection with lean manufacturing, as illustrated by Womack [38], following the "just in time"-philosophy.

Logistics - Logistics management is that part of supply chain management that plans, implements, and controls the efficient, effective forward and reverses flow and storage of goods, services and related information between the point of origin and the point of consumption in order to meet customers' requirements [151].

Mercantilism - (Economics) Also called mercantile system Economics a theory prevalent in Europe during the 17th and 18th centuries asserting that the wealth of a nation depends on its possession of precious metals and therefore that the government of a nation must maximize the foreign trade surplus, and foster national commercial interests, a merchant marine, the establishment of colonies, etc. [152]

Minimal cut sets –The least number of basic events that need to occur to cause a top (hazardous) event [88].

Mitigate – To mitigate is to make something (or become) less severe or harsh; moderate [152].

Ontology - An ontology can be described as by Howe [138] as:
1. (philosophy) A systematic account of Existence.
2. (artificial intelligence) (From philosophy) An explicit formal specification of how to represent the objects, concepts and other entities that are assumed to exist in some area of interest and the relationships that hold among them.
3. (information science) The hierarchical structuring of knowledge about things by subcategorising them according to their essential (or at least relevant and/or cognitive) qualities.

Resilience – Resilience can have two meanings [150]:
1. The ability to recover quickly from illness, change, or misfortune; buoyancy.
2. The property of a material that enables it to resume its original shape or position after being bent, stretched, or compressed; elasticity.

Risk - Risk may be defined according to industry standards, as: *a triplet of scenario, frequency and consequence of events that may contribute negatively* [55].

Risk acceptance criteria (RAC)- criteria that are used to express a risk level that is considered tolerable for the activity in question [147]

Robustness and flexibility - Sheffi [26] argues that there in essence are two strategies to coping with disruptions; robustness and flexibility. Robustness is the ability to withstand threats, flexibility is the ability to reconfigure system resources in possession to restore and uphold the ability to perform the mission.

Supply chain - *A supply chain 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.*

Supply chain management - Supply chain management encompasses the planning and management of all activities involved in sourcing and procurement, conversion, and all logistics management activities. Importantly, it also includes coordination and collaboration with channel partners, which can be suppliers, intermediaries, third party service providers, and customers. In essence, supply chain management integrates supply and demand management within and across companies [151].

Supply chain mission - The 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.*

Supply chain resilience - 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. [57]. Resilience is *the ability of the supply chain to handle a disruption without significant impact on the ability to serve the supply chain mission*. Resilience is about handling the consequences of a disruption, not about preventing a disruption from occurring. However, the effort to create a resilient system is made before a disruption occurs.

Supply chain vulnerability - Vulnerability is defined as: *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 [52].

Threat – treated as a synonym of hazard

Uncertainty - The state or condition of being uncertain, i.e. that the true value is not known. [152]

Appendix A: Selected papers

Paper 1
BERLE, Ø., RICE JR, J.B., and ASBJØRNSLETT, B.E., *Failure modes in the maritime transportation system – a functional approach to throughput vulnerability*. Maritime Policy and Management, Forthcoming. [48]

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Paper 2

BERLE, Ø., ASBJØRNSLETT, B.E., and RICE, J.B.J., *Formal Vulnerability Assessment: A methodology for assessing and mitigating strategic vulnerabilities in maritime supply chains*. Reliability Engineering & System Safety, 2011. **96**(6): p. 696-705. [49]

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Formal Vulnerability Assessment of a maritime transportation system

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ABSTRACT

World trade increasingly relies on longer, larger and more complex supply chains, where maritime transportation is a vital backbone of such operations. Long and complex supply chain systems are more prone to being vulnerable, though through reviews, no specific methods have been found to assess vulnerabilities of a maritime transportation system. Most existing supply chain risk assessment frameworks require risks to be foreseen to be mitigated, rather than giving transportation systems the ability to cope with unforeseen threats and hazards. In assessing cost-efficiency, societal vulnerability versus industrial cost of measures should be included.

This conceptual paper presents a structured Formal Vulnerability Assessment (FVA) methodology, seeking to transfer the safety-oriented Formal Safety Assessment (FSA) framework into the domain of maritime supply chain vulnerability. To do so, the following two alterations are made: (1) The focus of the assessment is defined to ensure the ability of the transportation to serve as a throughput mechanism of goods, and to survive and recover from disruptive events. (2) To cope with low-frequency high-impact disruptive scenarios that were not necessarily foreseen, two parallel tracks of risk assessments need to be pursued—the cause-focused risk assessment as in the FSA, and a consequence-focused failure mode approach.

1. Introduction

The World Economic Forum (WEF) 2008 Global Risk Report identified four emerging global risks—hyper-optimization and supply chain vulnerability, and energy supply security were two of them [1]. Integration of regional economies has come as a result of reduction in trade barriers and improvement in global logistics and technology. A result is that international and intra-regional trade growth rate has surpassed the global economy growth rate over the last twenty years. The above mentioned report asserts that effective preparation and management of supply chains may prevent contagion of a localized risk event—lack of sufficient preparation may amplify the disruptive impacts of events beyond the industrial sector into the societal domain. In particular, this is relevant in energy supply. Nevertheless, risks in long and complex supply chains are obscured by the sheer degree of coupling and interaction between sources, stakeholders and processes within and outside of the system; disruptions are inevitable, management and preparation are therefore difficult—in accordance with the Normal Accident Theory [2]. The WEF 2009 report upholds the warning—"*risk management must also account for interlinkages and remote possibilities. Low-probability, high-severity events, such as the terrorist attacks of 9/11, the Asia tsunami of 2004 and the current global credit crisis do happen*" [3].

Systemic risk in global infrastructure is emphasized in the 2010 report [4], page 23—"*a major terrorist attack that closed a port such as Rotterdam, Hong Kong or Los Angeles for weeks would have severe economic consequences on world trade because it would inflict major disruptions in complex just-in-time supply chains that comprise the global economy*". The conclusion from WEF is: "*there is a need to balance the additional private costs to operate more safely that might negatively affect the firm's bottom line with the benefits of reduced global risks; that is the trade-off between private efficiency and public vulnerability.*" The cost-efficiency or "lean" trend of the past 30 years [5], where organizations have minimized excess inventory and capabilities to cut cost, has made industry and society more vulnerable to disruptions in transportation systems—one may fear that some cost cuts have reduced the damage tolerance of systems.

Maritime transportation is a prerequisite for global trade, as over 80% of global trade in goods are effectuated by ships [6]. A general trend is that world merchandise trade grows two to three times faster than the world economy, represented by the global gross domestic product. The multiplier effect may be

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explained through globalized production and trade in parts and components, greater economic integration and deeper and wider global supply chains. Seaborne trade accounted for 8.17 billion tons of trade, where dry cargos (except bulk) represented 40% of volume, oil 34% and dry bulk 26%. The growth rate of the world seaborne trade was about 3.6% in 2008, down from 4.5% in 2007 due to the recent financial crisis.

The industrialized world, thereby including the European Union, USA, Korea and Japan, is increasingly dependent on imported natural gas, whereof an increasing share of these imports is liquefied natural gas (LNG). Security of energy supplies is a complex field, involving political, economical and military policies, as well as logistics and supply chain issues, and is of vital interest to all industrialized nations.

Through reviews, little research has been found on the disruption vulnerability of Maritime Transportation Systems (MTS). To gain insight into the practitioners' perspective, 20 semi-structured interviews were made with stakeholders in the LNG industry, port authorities, coast guards, terminal operators and support services for the maritime industry. A majority were located throughout the US and Panama, the remainder in Norway. General insights were as follows:

I1—respondents have an operational focus; in this, they spend their efforts on frequent minor disruptions rather than the larger accidental events.
I2—stakeholders do know that larger events do happen, and they know that these are very costly, yet they do not prepare systematically to restore the system.
I3—MTS stakeholders find their systems unique. As a consequence, they consider that little may be learnt from benchmarking other MTS' efforts in improving vulnerability reduction efforts.
I4—there seems to be little visibility throughout the maritime transportation system.

This research was triggered by the observation that major disruption risk in supply chains and transportation systems is a field that is not yet described in academic literature. Through interviews with industry stakeholders, respondents gave lack of understanding, methods and frameworks, as well as resource constraints, as reasons for not devoting time to seek to reduce the vulnerability of transportation systems of large scale supply chain risks. This leads to the following research questions:

RQ1—what would be a suitable framework for addressing maritime transportation system vulnerability to disruption risks?
RQ2—which tools and methods are needed for increasing the ability of operators and dependents of maritime transportation to understand disruption risks, to withstand such risk, and to prepare to restore the functionality of the transportation system after a disruption has occurred?

Through this conceptual paper we seek to meet the challenges posed by the WEF, by applying insight from methods and frameworks well known and tested within safety and reliability engineering on maritime supply chain risk management problems. Society's reliance on maritime transportation mandates that understanding how these systems may break down, and how to quickly restore the ability to move goods, is an important task. The Formal Safety Assessment (FSA) framework [7] provides the structure for the proposed vulnerability assessment, while the concept of failure modes [8] is used to prepare the system to handle unexpected hazards and threats and low-frequency high-impact scenarios.

In the following chapters, a literature review is presented in Section 2, relevant concepts in Section 3, the Formal Vulnerability Assessment framework is presented in Section 4, before discussions with a case and conclusions are given in Sections 5 and 6.

2. Literature review

2.1. Definitions

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 defined as *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 [9].

Risk may be defined as *a triplet of scenario, frequency and consequence of events that may contribute negatively* (in this case to the transportation system's ability to perform its mission [10]). A hazard is *a source 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. [11]. 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.*

Supply chain resilience has become a field of research the past 10 years, and a number of definitions have been made, [12,13]. In this paper, resilience is defined as *the ability of the supply chain to handle a disruption without significant impact on the ability to serve the supply chain mission.* Resilience is about handling the consequences of a disruption, not about preventing a disruption from occurring. However, the effort to create a resilient system is made before a disruption occurs. A good understanding of system failure modes can be relevant for this.

Failure modes are defined as *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 [14].

2.2. Previous research

Recent broad reviews of academic supply chain risk management papers include Rao and Goldsby [15], who present a typology of risks based on reviewed papers, Vanany et al. [16], who sort papers based on types of risk and industry sector, and Tang [17], who develops a framework to classify supply chain risk management literature into supply, demand, product and information management. Tang also offers a review on quantitative methods in supply chain risk management. Kleindorfer and Saad [18] develop a conceptual framework for managing supply chain disruption risk, stating that sources of risks need to be specified, assessed and mitigated. Zsidisin et al. [19] structures supply chain risk assessment techniques, in particular with an agency theory perspective—the message is that business continuity planning methods may be used to manage supply risk.

Manuj and Mentzer [20] bring together concepts from logistics, supply chain management, strategy, operations and international management to propose a five step framework for comprehensive risk management and mitigation in global supply chains. This is comparable to the FSA method, except the fourth step, where cost/efficiency is not the sole parameter. Rather, they include factors such as complexity management and organizational learning in addition to performance metrics. Manuj and Mentzer present seven risk management strategy categories—avoidance, postponement, speculation, hedging, control, sharing/transferring and security, although they stress that these are closely related.

Risk assessment methods, as shown above, are in general focused in identifying sources. Nonetheless, transportation systems are inherently vulnerable and disruptions do occur—source focused risk assessment approaches cannot prepare to mitigate all risks; transportation systems must therefore also be prepared to restore essential functions.

Limited research exists on the overall maritime supply chain vulnerability. Carbone and De Martino [21] discuss the role of ports in supply chain management, with a practical case on Renault using the port of Le Havre, France. Bichou and Gray [22] argue that ports are an integrated part of supply chains, and that they should be treated as such. Further, they argue benchmarking is possible between ports and other intermodal connection points, and that this has an underutilized potential, which is in line with I3. De Martino and Morvillo [23] investigate the interaction and interdependence between port stakeholders, as well as the change of ports from movement of cargo to value added logistics services.

Barnes and Oloruntoba [24] discuss the role of security in maritime supply chains, identifying weaknesses in security oversight, such as the lack of oversight in vessel registration and ownership and the use of flags of convenience. The contents of central security programs, such as the International Ship and Port Facility Security (ISPS) Code are presented in the context of maritime supply chains. The remainder of this paper is relevant to their suggestions for future research in proposing a framework for "identifying generic vulnerabilities in critical infrastructure at major ports", evaluating the current status of port-based institution, and assessing low-frequency high-impact scenarios.

Supply chain disruptions are unavoidable, the severity depending on the number of entities (nodes) affected. Supply chain density, supply chain complexity and node criticality may serve as explanatory variables for severity of a disruption to the supply network and how it spreads; see e.g. Craighead et al. [25] and Juttner [26]. Mitigation depends on visibility, recovery and warning capabilities; see Rice and Caniato [27] and Asbjørnslett and Rausand [9]. The industrial cost of larger disruptions is significant; Hendricks and Singhal [28] found that the abnormal stock return in the two years following disruption announcements were −40%, and the equity risk was 13.50% higher in the year following the disruption than the year before. Societal cost of supply chain disruptions is particularly high for critical goods such as energy [29]. Seen in light of the known high cost of disruptions, both to industries and society, efforts to understand supply chain vulnerability and to quantify costs are needed and timely.

3. Relevant concepts

3.1. Maritime transportation system—system definition

The sea transport part of maritime transportation is configured in the following three ways: (1) liner, (2) industrial and (3) tramp shipping. Liner services primarily moves goods such as containers according to fixed itineraries and schedules, much like a bus. Industrial operators own and manage their own fleet, seeking to minimize costs. Tramp shipping follow cargos like taxis, focusing on profit maximization [30]. Fleet size and mix, as well as routing and scheduling of vessels, is vital in securing the profits of stakeholders in the MTS. To achieve this, the usage of vessels must be optimized; see reviews by Ronen [31,32] and Christiansen et al. [33]. Optimizing over a chain, production capacity and storage must be included. Grønhaug and Christiansen [34] describe a solution to an inventory routing problem for an LNG supply chain.

The maritime transportation system as a whole can further be described as being composed of five elements. A set of "port objects", involving ports, terminals, intermodal connections and navigable waterways, as well as a set of vessels constituting the shipping networks, as described above, can describe the maritime transportation system (Fig. 1).

Understanding of the transportation system from a supply chain operator's perspective can be made at several system levels. A vessel operator controls a fleet of vessels, composed of single vessels with a set of characteristics. Similarly, the land side can be understood as a system of ports both on a local, national and regional level. The individual ports have several terminals, serving different types of loading technology and cargo. Maritime transportation systems need to be understood as a part of a larger industrial system, as well as the provider of societal supply needs. If disruptions in a port or terminal go beyond the buffers, ripple effects can spread to the greater economy leading to wider shutdowns. Given the limited number of nodes, e.g. ports and terminals in a system, failures may spread beyond foreseen limits; see Table 1 for an example.

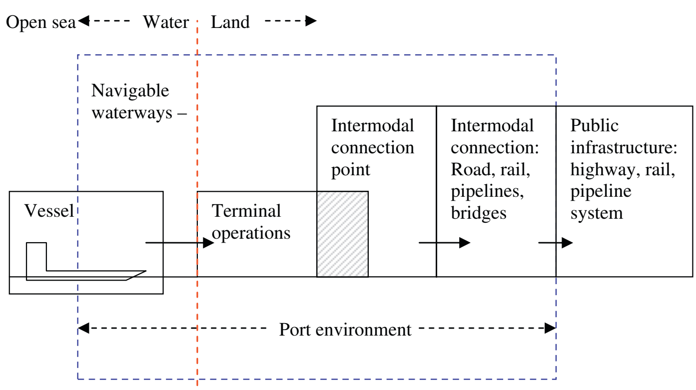

Fig. 1. Sea-land interface of maritime transportation system [4].

3.2. Failure modes

By preparing to restore the ability of the system to transport goods, the system may be better equipped to handle low-frequency high-impact scenarios. Through combining the critical way a transportation system may fail with the elements of the transportation system; the failure modes of the MTS are identified [14]; see Table 2. These describe the key functions and capabilities that are necessary for the system to perform its mission.

The critical ways a transportation system may fail 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: supply capacity is the ability necessary to source provisions needed for the element to perform its function; for a factory, this is inbound materials, utilities and electricity. Financial flows cover the ability to access capital and liquidity/cash flow. Transportation is the ability to move materials, including those presently at work. Communication would include enabling technology, and is vital for transparency in the supply chain. 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?

Table 1
Levels in maritime transportation system.

Component	Example failure
System of local, national and regional ports	Failure of coordination on development of regional and national infrastructure, e.g. not planning for alternative ports for critical cargos
Port	Natural disasters removing usability of an entire port, such as 1995 port of Kobe earthquake [35]
Terminal	Failure of vessel loading system

3.3. Formal safety assessment

Quantitative risk assessments have been used in a variety of industries. In the maritime context, Formal Safety Assessment (FSA) is made to describe a rational and systematic risk-based approach for safety assessment [7,36]. While FSA for maritime applications could be criticized, see e.g. Kontovas and Psaraftis [37], there is much to gain by linking safety and reliability engineering to maritime risk assessment, and for applying FSA beyond vessel risk assessment to understanding vulnerabilities in maritime supply chains.

Benefits of the FSA include that it is a tested and already established method, and that there is considerable knowledge about the method in the maritime sector. Drawbacks take in that the framework is dependent on expert judgment for quantification, uses simplifications in ranking of risks, allows for use of a variety of methods in the steps and that it can be manipulated. However, these objections do not exclusively apply to FSA; they could also be relevant for other methods.

3.4. Requirements of framework for addressing disruption vulnerability for maritime transportation system

The research questions were divided into the following two aspects: (1) identifying a framework for addressing the disruption risk to the system, and (2) identifying approaches, tools and methods to support this framework. Based on the literature, in particular Oehmen et al. [38] and Kontovas and Psaraftis [37] and

Table 2
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 super-structure	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	Ability to move equipment and people within and through port	Ability to move goods and people within terminal	Equipment for moving and transloading goods to surface transportation, e.g. trucks and trains	Ability to move goods and people within and through the navigable waterways	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 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	Ability to move and position vessels, maintain safety and security, invest, develop and market port	Loading/unloading, processing, documentation, capacity	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

interviews with stakeholders, the requirements to a framework can be defined as follows:

R1—the framework must be structured and systematic, with explicit declaration of responsibility for the framework and for updating it.
R2—the framework must support quantification of risks.
R3—the framework must anticipate risks and prepare for the unexpected.
R4—the framework must be explicit on cost/benefit assessments of risk; both the business and the economics side of risk management should be considered.
R5—the framework must be transparent.
R6—the framework should give room for future implementations of dynamic monitoring of vulnerability, e.g. risk influence modeling.

4. Formal vulnerability assessment

To shift the FSA framework into risk management in design and operation of maritime transportation system, the additional risk picture will have to be understood. Hazards and threats may destroy the transportation systems' ability to deliver goods, which may harm both the involved stakeholders, as well as the society, which is dependent on the flow of goods.

The outline of the suggested assessment is presented in Table 3. The original FSA method is analogous to the left flow in the figure; the steps are the same in the proposed FVA. The two paths may be termed the hazard path and the mission (consequence-focus) path. Details about the steps are described in the discussions in part five.

As seen, the system definition and recommendation steps are shared between the hazard focus and the mission focus paths, as the overall goal is to decrease the vulnerability of a given transportation system. However, the frequent risks are treated in the hazard path, while the LFHI-risks are treated in the mission path. In this, the goal is to have a separate focus on LFHI-risks without being caught in the details of daily operation.

5. Discussion and cases

The Formal Vulnerability Assessment can be illustrated using the LNG transportation industry as an example: To increase the understanding of the operational context, four of the interviews made were with stakeholders in the LNG industry, to gain insight into planning and operation of the LNG maritime transportation system.

5.1. LNG market background, characteristics and insights

World LNG production increased by 9% in 2007, making it the fastest-growing energy source, continuing the total growth of 53% the preceding 5 years [39]. The total 2006 volume of natural gas shipped as LNG was 215 billion cubic meters (bcm), a number the International Energy Association (IEA) expects to increase to 300–320 by 2010.

For the LNG shipping industry, contracts and sales is a relevant factor. Traditionally, piped natural gas is sold on contracts involving some sort of a Take-or-Pay contract [40,41], while LNG is sold on long term (often 20 years) fixed contracts. However, the market is rapidly changing, in particular through the emergence of a global spot market for LNG. The International Group of Liquefied Natural Gas Importers claims that the spot and short-term (less than 4 years) contracts in 2007 amounted to 586 cargoes, 20% of the total amount of loads [42].

Drivers of the LNG markets include the introduction of larger and more cost-efficient vessels, the general high growth rate of the LNG industry and European diversification from Russian piped gas. The North American markets were long expected to be major markets, though the US shale gas development projects may lower the need for increased LNG imports.

A particular feature of the LNG industry is the high cost of infrastructure. To reduce capital and operational expenses, LNG supply chains are optimized to a high degree, leading to lean and tightly integrated systems with little slack. This is in essence what the WEF presents in the 2008 "Global Risks" report, fear of over-optimization and energy supply security [1]. In the LNG case, these two are coupled. In particular, this analysis is relevant to study energy import dependencies, as current LNG supply chains are optimized to the level that much of the system storage and flexibility can be found in the shipping element, lacking on-shore infrastructure [39,43]. The IEA claims that natural gas supply security is deteriorating through lack of field development, growing dependence on imported gas and longer transportation routes, in addition to growing worries of creation of a "Gas OPEC" [44].

From the four interviews with LNG shipping stakeholders, insights particular to the LNG market were as follows:

I5—cost drivers of the LNG industry were liquefaction, storage tanks, vessels, terminals and technology development. Primary factors affecting robustness were utilization factors of the liquefaction plant, export harbor storage and number of export harbor berths; the crucial resilience factor was the possibility of recursive optimization plans for vessels and inventory.
I6—rigorous deterministic planning is made for a stochastic system. There is large variability in demand, and tight requirements to booking. Some plans must be completed up to 18 months ahead; this is for instance the deadline for some LNG receiving terminal.
I7—flexibility is not introduced in the system design; resilience is added through introducing slack. However, given the cost of excess capacity, redundancies in inventories can only cover minor incidents.

While significant resources are spent to operate the transportation systems more efficiently and to fulfill contracts, informants consistently reported that planning for large scale disruptions was not done in a systematic way; the focus was to reduce the likelihood for events occurring, where added slack was intended

Table 3
Outline of FVA process.

	Hazard focus	Mission focus
Step 0—preparation	0—define system, parameters, criteria, borders, etc.	
Step 1—hazard identification	1a—what may go wrong	1b—which functions/capabilities should be protected
Step 2—vulnerability assessment	2a—investigation/quantification, most important risks	2b—investigation/quantification, all relevant failure modes
Step 3—vulnerability mitigation	3a—measures to mitigate most important risks	3b—measures to restore functions/capabilities
Step 4—cost/benefit assessment	4a—cost/benefit assessment	4b—cost/benefit assessment
Step 5—recommendations for decision making	5—recommendation and feedback to assessment	

for additional buffers. One informant expressed that the planning branch had commenced scenario work, but lacked the tools and managerial commitment to price vulnerabilities and to implement potential measures.

5.2. Exemplary FVA assessment of LNG maritime transportation system:

In the following, some exemplary elements of the proposed FVA assessment on the generic LNG transportation system are drawn out, including insights from interviews with industry stakeholders. For context relevant insight into the FSA methodology, Vanem et al. [45] has performed a thorough review of safety risks in LNG carrier operations.

5.2.1. System description

The preparatory stage of this assessment should include a thorough description of the system—identifying the inherent capacities of the system, as well as relevant constraints. It is vital for the stakeholders to share an understanding of the system, to create a foundation for further discussion. The focal stakeholder should be clearly defined—whose business is the assessment meant to improve. Likewise the scope of the system, how comprehensive it should be, and the borders of the system should be clearly defined. For the exemplary FVA of an LNG transportation system, the components can be described as in Fig. 2 and Table 4.

Optimization of LNG inventory is necessary to ensure cost minimization. Operational constraints, as described by informants, include tank levels, security margins, production and consumption rates, vessel capacities and speed, number of berths with loading gear, etc. The optimization approach is deterministic, with fixed plans and delivery programs made up to 18 months before delivery. However, the problem carries stochastic characteristics. There is variability in demand, transit times for vessels, as well as general delays for disruptions. These are not well covered in the optimization of the sea transport system, fleet of vessels as well as the supply chain interlinkages. Vessel ownership introduces other constraints, as not all are owned by the LNG supply chain operator, although these constraints may be relaxed in abnormal situations. Some are owned by several owners, introducing requirements that all vessels should be used equally much. Other constraints are political. Pooling of resources, as found in for instance the container shipping industry, is not common. In general, vessels are very seldom redirected once sent, nor are they sent out with half loads—this sets the industry apart from e.g. crude shipping.

Clearly defined risk acceptance criteria allows for objective selection of which risks and resulting vulnerabilities should be accepted and which should not. As mentioned by the World Economic Forum, there is a need for a trade-off between private efficiency and public vulnerability—risk acceptance criteria should include measures for both individual (supply chain) and societal risks [46]. For instance, accepting higher degree of optimization and decreasing buffers may be beneficial for the operators of an LNG transportation system, at least in the short term. Society, dependent on natural gas imports, is exposed to the consequences of missed delivery. Parameters that could be included in the risk acceptance criteria discussion include price, quality and continuity plans; see e.g. Tang [17].

As an example, As Low as Reasonably Practicable (ALARP)-criteria [47] could be used for this assessment, creating a triage of risk into acceptable, unacceptable and ALARP-risks. The latter are risks that should be reduced as long as the cost of implementing measures compared to benefits gained do not exceed a given upper limit. An initial assumption is that most risks identified will either be acceptable, or will need cost/efficiency evaluations owing to being in the ALARP area. Metrics to define what is acceptable risk to the stakeholders will need to be quantified in the system description, Examples include metrics such as Value-at-Risk (VAR), which aims to provide a single risk metric for the financial loss of a portfolio of given assets; see e.g. Allen et al. [48] for an extensive review. Supply-at-Risk [49], which is a modification of VAR for supply portfolios, could serve as a metric for acceptable supply loss both for industry and society at large.

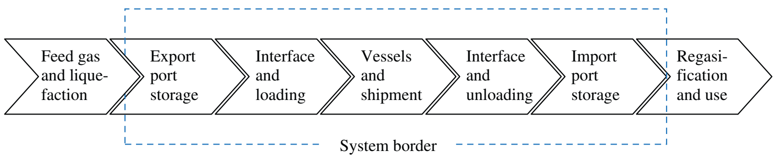

Fig. 2. Components and border of LNG transportation system.

Table 4
Components of LNG chain.

Components	Description	Characteristics	Goals/challenges
Feed gas	Natural gas from fields	Transported in pipelines	Steady usage
Liquefaction plant	Cleans and cools gas to liquid state at $-161\,^{\circ}C$	High investment and operational cost	Maximize utilization without interruption
Export storage	Storage of LNG before loading	High investment cost	Minimize required capacity
Loading	Moving LNG to vessel	Specialized infrastructure	Safe loading, maximize throughput capacity
Port/vessel interface	Scheduling and coordinating of vessels	Vessels serve as storage in system	Minimize time for berthing
Shipping network	Owned, chartered (and spot) vessels	Decisions on utilization of owned and chartered fleet	Maximize profits, recourse action for deviation management
Port/vessel interface	Scheduling and coordination of vessels	Planned delivery of gas	Minimize time for berthing
Unloading	Moving LNG from vessel	Specialized infrastructure	Safe unloading, maximize throughput capacity
Storage	Storage of LNG	High investment cost	Minimize capacity requirement
Regasification	Evaporating LNG to natural gas	Moderate investment	Meet gas demand without interruption
Gas consumption/gas storage	Use of gas, gas to transportation system, gas to storage	Variability in demand with stochastic uncertainty	Meet gas need

According to informants, the system design has still not reached maturity; design parameters of the system have been selected with imperfect information, particularly regarding the system's ability to cope with operational variability and uncertainty. The industry experiences rapid growth; contracts of delivery are typically made for 20–30 years, while empirical knowledge of such systems have been lacking. Challenges with respect to inventory routing are a result of this. One system had tank capacity of only three days of production between empty and full storage—if full, the production of the liquefaction plant had to stop. There seems to be a separation between operational planners and those making investment decisions with regards to investing in infrastructure and balancing capacities through the supply chain. Technical robustness is contrary; vessels are strictly maintained with frequent service intervals, leaving almost no disruptions due to vessel breakdown.

5.2.2. Hazard identification

5.2.2.1. Hazard focus. The common approach to risk management, which is seen both in the FSA, in the reviewed supply chain risk management literature and as described by industry stakeholders, is to try to list all conceivable risks, sometimes helped by a source categorization. For the proposed framework, the ambition is to cover frequent and readily apparent risks. Investigating historical data on previous incidents is typically the first step, in addition to structured brainstorming sections with practitioners. A typical approach in safety and reliability engineering involves that screening of hazards should be performed to identify which hazards should be treated further, and the number should depend on the resources available for the result; irrelevant hazards should be removed.

According to reviews and informants, the LNG shipping industry does not have documented extensive experience with supply disruption, given the small scale of the systems until recently. Rapid growth and technological development limits the availability of empirical data on chain disruptions. This curbs such assessments to methods such as expert judgment and structured breakdown of the systems, possibly aided by existing frameworks on risk sources. Another option is the use of simulation to identify weak points of the system; see e.g. Kleijnen [50] and Kleijnen and Smits [51].

5.2.2.2. Mission focus. What are the key functions and capabilities that the system relies on to be able to perform its mission, that is, to be able to move goods and protecting the dependents of the system from disruptive events? The failure modes in Table 1 offer guidance to the key functions of the transportation system. Depending on the scope of the assessment, not all elements of the maritime transportation system may directly be relevant; loss of any of these may still impact the transportation system. A system wide assessment should be performed, where the failure modes provide a structure for breaking down the system. Stakeholders with insight in each failure mode should continue the assessment for these, specifying infrastructure, equipment, processes, personnel needed, as well as identifying how the function relates to the system's ability to move goods. It is relevant to see whether there is something not covered, and if all personnel performing assessment understand the failure modes.

5.2.3. Risk assessment

5.2.3.1. Hazard focus. As for the FSA, step two should investigate all hazards identified as relevant. Methods are not specified, other than that identified relevant risks, their causes and consequences should be well understood through the use of appropriate risk assessment methodologies. In FSA, the risk assessment is often divided into a qualitative and a quantitative part [7]. Qualitative methods for exploring risks could be influence diagrams, e.g. showing interrelations between regulatory, operational and organizational influences, etc. Quantitative methods include fault and event trees and Bayesian Belief Networks, where barriers that prevent events from occurring or mitigate consequences should be included. Quantification of probabilities and consequences lay the foundation for cost/efficiency calculations.

Quantification of risks in the LNG industry can be done through making fault and event trees for hazards; see Vanem et al. [45] and Trbojevic and Carr [52] for examples. However, lacking empirical data and experience with operation of rapidly evolving maritime transportation systems, not all factors will be uncovered, nor can all hazards and threats be treated; insignificant risks should not be pursued. For instance, scenarios such as vessel collisions, mooring failures and extreme weather are tangible and may be pursued further. Security-related events should also be treated according to its expected occurrence; e.g. piracy in the horn of Africa-region is more likely than bombs planted aboard vessels. Discrete event simulations as well as expert judgment may be used to generate data. It is important that low-frequency risks, as well as not foreseen threats will not be included by typical FSA selection criteria; the failure modes set out to cover this aspect.

5.2.3.2. Mission focus. For each identified failure mode, the purpose of the analysis is to understand the function and its effect on the system's ability to perform its mission. For instance, communication in ports has several elements—phone lines, mobile phone networks, radio communication systems, intra and internet connectivity, as well as database and data management systems. What would the consequence of a loss of any of these be to the throughput mission of the supply chain?

Identifying barriers help creating an understanding of the system's ability to cope with disruption. For a supply chain context, barriers may be understood through an analogy to reliability engineering [53]. Passive barriers include buffers such as extra storage of goods, excess transportation capacity and hardened infrastructure, as well as parallel terminals and ports. Functional barriers may be factors such as having made contingency plans, having prepared contracts for alternative suppliers of services, etc. Symbolic barriers could encompass e.g. early warning signals within planning systems. Non-material barriers include the industry and organizational culture; are there organizational procedures present in case of a disruption, and have people been trained to handle disruptions?

Consequences of loss of failure modes can be understood through using event trees, where the barriers are those events that may prevent the most severe consequences. One example is below in Fig. 3. Loss of a loading berth is used as an example; consequences are illustrated for export port and import port at a high level. Going into more detail, consequences could be broken down to vessel-owner, terminal operator, customers, etc. For example purposes, consequences have been broken down to major and minor consequences, depending on whether LNG production or gas consumption have been harmed (major) versus only incurred extra cost (minor).

Given that probabilities are unknown with the failure modes, criticality cannot be determined through multiplying probability and consequence. Rather, the cost of loss of the function could be used. Quantification of risk may be done through the simulation and optimization models of a maritime supply chain. A ranking of criticality of partial and complete loss of failure modes should be made as input for prioritization of mitigating measures, starting from a qualitative "what if"-analysis to using simulation methods.

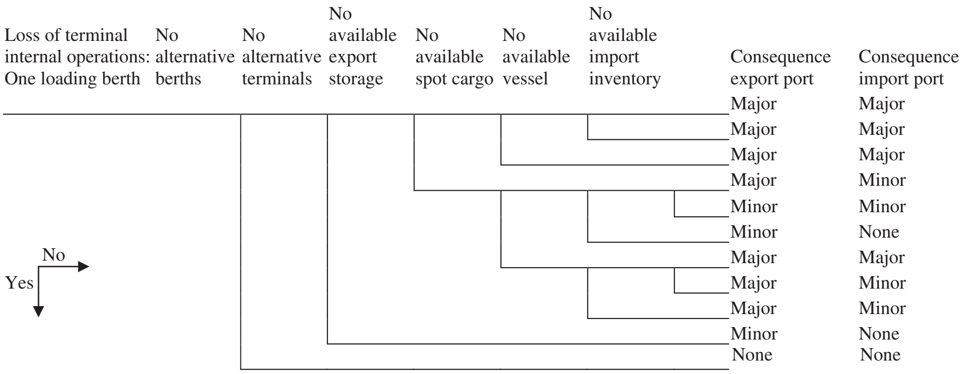

Fig. 3. Event tree for loss of terminal internal operations.

5.2.4. Mitigating risks

5.2.4.1. Hazard focus. The result from the risk assessment stage is, as in the FSA, a systematic oversight over major risk, contributing causes and potential consequences, including the barriers that may reduce probabilities and consequences. Individual risks can be compared up against risk acceptance criteria, supporting ALARP and VAR approaches. The goal of this step is to further identify measures that may mitigate relevant risks. In FSA assessments, risk control measures are grouped into risk control options to simplify selection and to minimize overlap of measures.

5.2.4.2. Mission focus. Business continuity plans for all identified failure modes, where arrangements to restore important functions and capabilities are included, is a robust approach to prepare for risks that have not been treated in the hazard focus approach. Assessments of dependency on other functions may reveal weak points in the supply chain, and possibilities to mitigate any such. For instance, established emergency coordination plans between ports, both nationally and regionally, may facilitate restoration of transportation capacity, although a single port may lose its throughput capacity. Informants reported that business continuity planning was not frequently used in the US for cost saving reasons, partially due to the competitive situation between ports. However, larger terminal operators with setups in several ports stressed their ability to reroute goods and vessels fast between their own terminals. Effectiveness of potential business continuity plans should be evaluated as for mitigating measures.

Another example is that one informant reported the problem of using loading gear in a terminal without electricity provided by the grid, while reporting previous utilities outages. Would secondary power supplies, such as generator capacity, allow for operation of a terminal to full or partial capacity? A key issue is to quantify the robustness of as well as the effect of the loss of failure modes—how significant would this be for the system's ability to operate, how much time and resources are required to restore the failure mode and what other input is necessary for doing so?

5.2.5. Cost/efficiency estimation

Cost/efficiency estimations require identifications of relevant costs and relevant benefits, which is an intricate task [54]. Both of these are subject to considerable uncertainty; costs are not only investment, but also running costs through a life-cycle perspective. Benefits can be indirect, hard to measure and may in some cases only be identified after a disruption has occurred. Methods to provide quantitative data include heuristics, scenario analyses, benchmarking and sensitivity analyses. However, due to lack of precise data, expert judgment in parallel with simulation may prove the most accurate assessments tool at hand.

The cost–efficiency estimation needs to consider the societal interest in critical infrastructure. While a measure may be unprofitable for the individual supply chain operator, it may be cost-beneficial from a societal perspective. To ensure that the interests of society are included, supply contracts may specify risk higher acceptance criteria and/or compensate the operators for reducing supply chain vulnerability, for instance through introducing additional buffers.

5.2.5.1. Hazard focus. Cost-benefit assessments of risk control options compare the vulnerability reduction gained from each option with the cost of implementation. Explicit cost/efficiency estimations are what set FSA-based frameworks apart from others. The traditional measure is whether benefits are higher than the implementation cost, using a Net Present Value (NPV) criteria, following Saleh and Marais [55]. Benefits include reduced number of disruptions, reduced impact from each disruption, and increased availability of assets. Costs include investment, operation and training expenditures. A value based ranking of options could be made to simplify selection, using for instance cost–benefit ratios, capital investment and operational expenses as criteria.

5.2.5.2. Mission focus. Identifying the cost of disruption by multiplying probability and consequence is more difficult for the failure modes than in the FSA, as the probability of delays or failure is hard to estimate. However, the cost of system failure, both entirely or partially, can be estimated, and is probably the most accurate valuation available. This may be both the direct loss through contract breaches and spot prices to cover volumes, to immaterial assets such as reputation. Similar to the hazard focus, a cost-based ranking of measures may be the best available estimate.

Furthermore, investments in flexibility could provide benefits to normal operation. For instance, operating a homogenous fleet of standard size (130–160 000 m^3) LNG vessels would take away scale effects of using larger tankers. However, all vessels would be able to serve all ports, which offer more flexibility in routing. Larger vessels such as the 210 000 m^3 Q-flex tankers can only serve about two-thirds of the world ports, and the 260 000 m^3 Q-max tankers can only serve about half, both with some modifications of ports [56].

5.2.6. Recommendations for decision making

An objective comparison of the identified options, as for the FSA, should be made based on potential reduction of vulnerability, both to frequent and infrequent risk. The recommendations for decision making should be a synthesis of the formal process, selecting which measures to include. For instance, interviews reveal that deterministic optimization of inventory and routing of vessels does not include the stochastic nature of an LNG transportation system. Furthermore, there seems to be a too strong separation between the investment part and operational planning part of the system. Rather than investing in more flexibility in the system, for instance through allowing complete rerouting the fleet after incidents, planners are forced into leaving margins in the system, such as setting a cap for tank loading and emptying.

Larger disruptions cannot be mitigated by such buffers, as they have no effect after these are exhausted—allowing rerouting of vessels and cargos would decrease the likelihood of having to shut down production. This requires interchangeable vessels and cargos, flexibility on the customer side and a routing system able to identify such changes. Currently, cargo swaps are ‘‘almost never’’ performed (informant). Furthermore, when done, a criterion has been to have as few changes to the existing annual delivery plan as possible, although additional permutations would create more cost-efficient solutions.

Feedback to the earlier process includes suggestions for improving the process, such as increased detail level in specifying failure modes. Recommendations for follow-up and reviews of the assessment should be specified. If possible, insight from the assessment should be used as input in creating better indicators of anomalies in the system; an effective early warning system may significantly reduce the impact of a disruptive event.

5.3. General discussion

The conceptual framework meets the requirements presented. Following the FSA, it is structured and systematic with explicit responsibilities (R1), supports quantification of risks (R2), anticipates risk and prepares for the unexpected (R3), promotes an explicit cost/benefit assessment (R4) and is transparent in describing the assessments made (R5). Dynamic monitoring of vulnerability is currently not prevalent in maritime supply chains; implementation is a topic for further research. The authors believe the framework can accommodate dynamic monitoring, hence supporting (R6).

Existing supply chain risk management frameworks tend to focus on mitigating sources of risk. However, following Craighead et al. [25], disruptions are unavoidable, and supply chain stakeholders should set up continuity plans to recover the key functions the transportation system depends on [19]. In particular, for the maritime transportation system, existing research is fragmented. Comparatively much research exists on security, although the consequences of a security breach may result in similar consequences as other sources, such as technical or systemic hazards, or natural disasters.

Negative spillover effects [54], affecting those who are not directly involved, is relevant in discussing supply chain risk management in global LNG transportation systems. The ultimate end users, dependent on delivery of LNG may bear the consequences of a disruption, given societal dependence on energy imports, as pointed out by the world economic forum [4]. Cost–benefit assessments can reveal different preferences for reliability between the transportation system stakeholders and society as the customer, allowing for realignment through contracts, as illustrated in Section 5.2.5.

The underpinning of this paper is that unconditional optimization, reduction of buffers and lack of investment in resilience will increase supply chain vulnerability. In particular, the MTS is relevant for societal supplies, due to the share of coal, crude oil and products, and LNG transported by sea. Disruptions in supply chains come at a high cost [28], justifying why coping with this vulnerability should be of high priority. By transferring insights from safety and reliability engineering, it may be possible to increase the understanding of how maritime transportation systems fail and how to cope with this. In particular, this paper responds to some of the suggestions for future research by Barnes and Oloruntoba [24] on creating indentifying critical vulnerabilities in ports and assessing high frequency low consequence and low frequency high consequence scenarios.

Limitations of the framework include that it has not been tested on an industrial system. Quantification and pricing of risk is a challenge, in particular for low-frequency high-impact scenarios.

6. Conclusions

There is a need for methodologies for assessing vulnerabilities in maritime supply chains, which allows for systematic and transparent identification and mitigation of vulnerabilities to the ability to move goods. Given that supply chains are increasingly complex and are dependent on, and have an impact on a number of stakeholders, getting a realistic overview of potential hazards and threats to the supply chain is a considerable task.

A Formal Vulnerability Assessment methodology may offer a transparent and systematic way to assess and systemize risks, both to evaluate the current state, as well as to allow for assessing the impact of changes to the existing supply chain. It is beneficial that the methodology is based on existing and tested methods. No current method, to the authors' knowledge, exists to assess mission-oriented vulnerability of maritime transportation systems. Through a comprehensive structuring of the current status of the system, a joint platform for a shared understanding between the stakeholders can be made. Then in turn, using both the hazard and the mission focus for addressing the vulnerabilities of the system, a wide spectrum of potential disruptive events has been covered. This conceptual approach is novel compared to reviewed supply chain risk assessment frameworks.

6.1. Future research

Applications of the FVA methodology need to be tested. In collaboration with industrial partners, an exemplary assessment will be made of a real industrial case. An interesting follow-up to a full FVA assessment to an LNG supply chain would be to test the methodology on other shipping segments, such as crude oil, container, car freight, chemicals, etc.

Quantification of risks for this assessment is still untested. In particular, modeling of the consequences, factors contributing to preventing severe consequences from occurring and modeling interaction between failure modes needs more research. One approach is using Bayesian Belief Networks to model influencing factors on risk.

A challenge for a real-world application is to determine indicators and metrics that allow for real-time monitoring of the risk levels of the supply chain, thereby allowing a continuous picture of the system's vulnerability. Risk influence modeling [57] and modeling of degradation of barriers could prove to be useful tools in this process. One example is a maritime transportation system with good fleet optimization software but weak planners—if training and increasing the competence of planners is not done, this would lead to a degradation of the human barriers over time, as the capacity to find flexible solutions to problems may be inadequate.

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Paper 3
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Optimization, risk assessment and resilience in LNG transportation systems

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Abstract
Purpose: This paper addresses how to systematically address vulnerability in a maritime transportation system using a Formal Vulnerability Assessment approach, create quantitative measures of disruption risk and test the effect of mitigating measures. These quantitative data are prerequisites for cost efficiency calculations, and may be obtained without requiring excessive resources.

Design/methodology/approach:
Supply chain simulation using heuristics-based planning tools offers an approach to quantify the impact of disruption scenarios and mitigating measures. This is used to enrich a risk-based approach to maritime supply chain vulnerability assessment. Monte Carlo simulation is used to simulate a stochastic nature of disruptions.

Findings:
The exemplary assessment of a maritime liquefied natural gas (LNG) transportation system illustrates the potential for providing quantitative data about the cost of disruptions and the effects of mitigating measures, which are foundations for more precise cost-efficiency estimates.

Research limitations/implications:
This simulation was done on a simplified version of a real transportation system. For resource reasons, several simplifications were made, both with regards to modeling the transportation system and with the implementation of the Formal Vulnerability Assessment framework. Nevertheless, we believe the paper serves to illustrate the approach and potential outcome.

Practical implications:
Practitioners are provided with an approach to get more precise quantitative data on disruption costs and cost/efficiency of mitigating measures, providing background data for decisions on investing in reduction of supply chain vulnerability.

Originality/value:
The combination of risk assessment methods and inventory routing simulation of maritime supply chain problems is a novelty. Quantifying vulnerability, effects of disruptions and effects of mitigating measures in maritime transportation systems contributes to a little-researched area.

Key words: Supply chain risk, maritime transportation, LNG, fleet routing and scheduling, Monte Carlo simulation.

1 Introduction
The World Economic Forum (WEF) publishes annual reports of present and emerging global risks. In 2008, energy security and hyper-optimization were pointed out as two of four emerging global risks (WEF 2008). Access to energy is essential for the world economy, where most countries rely on energy imports. WEF warnings about societal vulnerability to

disruptions in energy supply continue: “Risk management must also account for interlinkages and remote possibilities. Low-probability, high-severity events […] do happen“ (WEF 2009). Systemic risk in global infrastructure is emphasized in the 2010 report (WEF 2010): “there is a need to balance the additional private costs to operate more safely that might negatively affect the firm’s bottom line with the benefits of reduced global risks; that is the trade-off between private efficiency and public vulnerability.” The 2011 report emphasizes resource security, thereof energy, as one of five key risks to watch.

Natural gas supplies are critical for societies dependent on its use for industrial production and electricity generation, roughly 40% is used for industrial purposes and the US Energy Information Agency (EIA) expects that 36 % of all electricity generation in 2035 use natural gas (EIA 2010). A growing share of traded natural gas is transported on ships in the form of liquefied natural gas (LNG). EIA anticipates the shipped LNG volumes to increase 2.4 times, from 226 billion to 538 billion cubic meters between 2007 and 2035. LNG is natural gas cooled down into liquid form and thereby compressed 600 times. Shipment capacity of LNG increased from 5 million cubic meters in 1980 to 35 million cubic meters in 2007 and was expected to reach 55 million cubic meters by 2010 – total traded volumes reached 483 million cubic meters in 2010. These systems are complex and tightly interconnected, leaving them vulnerable to disruptive events. Failures in critical infrastructures may have large implications on society, and should be addressed appropriately (Utne et al. 2011).

The aim of energy security is to make sure that energy supply needs are covered, that these systems can withstand disruptions to supply and adapt to changes to minimize the impact on the end users. Although optimization is a general good, minimizing waste in the line of good resource management, unconditional optimization of production and transportation systems may introduce risks and expose vulnerabilities to the system’s ability to perform its mission.

Optimization tools allows for structured analysis of complex problems, where mathematical formulation of problems allow for efficient utilization of limited resources. Recent advances in algorithms and heuristics allow for design and operation of complex and more efficient global supply chains, exploiting synergies across geographic locations, supply chain functions and time (Shapiro et al. 1993). However, it is vital to recognize that optimization models solves the mathematical problem as it is formulated, “models do not replace human judgment” (Shapiro et al. 1993).

In particular, optimization tools for practical problems are typically designed to operate in a deterministic setting, assuming that the world is predictable, and that variability is limited. However, there is a growing focus on low-frequency high-impact scenarios, see e.g. (Berle et al. 2011a; Berle et al. 2011b; Hendricks and Singhal 2005; Kleindorfer and Saad 2005; Sheffi 2005a; Sheffi 2005b; Taleb 2007). These are the scenarios that very seldom occur, but when they do, they create large problems for the supply chain. The large number of such possible scenarios makes the total possible impact significant; although little can be done to prevent all these events from occurring. Extreme examples are the 1994 Kobe earthquake (Chang 2000) and the 2002 Los Angeles dock lockout (Sheffi 2005b), both with massive consequences to business and infrastructure. Neither of these are encompassed in the sort of problems where operations research [OR] methods are normally applied.

This paper addresses the gap between optimizing a transportation system based on mathematical models and supply chain risk assessment of these systems. In essence; can risk assessment methods be used to improve the handling of uncertainty in decision planning in large and complex supply chains?

Risk management encompasses as set of well-known methods to identify, assess and manage risks and uncertainties. Benefits of risk assessment methods include room for discussion of uncertainties, that experts may be used to fill in gaps in data, that the "world view" may accept that not all factors are known, and that quantification may be difficult, that it may require simplifications, and that calculations may be very costly in labor resources.

From the start, the operations research (OR) community worked with static and deterministic problems. This is relevant for many problems, and has contributed a great deal to resource utilization. However, the real world has considerable uncertainty associated with it. Also, if the problem is based on a real-life scenario, most likely new information and constraints will appear. If the model should still be relevant, it needs to be updated. In essence, types of OR problems can be divided along two axes: deterministic versus stochastic and static versus dynamic problems (Stålhane 2011). Stochastic is still a developing technology and calculations become complex and computationally demanding. Also, operations research methods do not easily include low-frequency high-impact risks.

To model a real life scenario, a stochastic model allows for investigating complex systems and including rare scenarios. Monte Carlo simulations introduce random numbers into a model. By repeating the analysis a large number of times, the properties of the system become evident. This paper uses risk assessment methods to determine what may go wrong in a maritime supply chain, and how to cope with disruptions. To determine the effects of disruptions and mitigating measures, Monte Carlo methods and operations research tools are used to quantify effects.

The purpose of the approach presented is not to give the final answer to how risk analysis and mathematical planning tools can be integrated. Rather, this is intended as a conceptual paper to present this novel approach. This paper is based on two research questions:

RQ1: Can risk assessment methods combined with results from fleet planning provide more insight in creating resilience in maritime supply chains?
RQ2: Does the combination of risk assessment methods and deterministic optimization software provide new insight for a supply chain planning problem under uncertainty?

Transportation of natural gas in its liquid state as LNG may serve as an illustrating example of society's dependence on maritime transportation systems and the vulnerability of such systems. High cost of investment in LNG supply chain infrastructure and operation provides a strong incentive to create lean and tightly coupled systems, to increase resource utilization, thereby minimizing cost.

In the following, definitions, relevant previous research and methods are presented in section two, the system definition and simulation setup in section three, results and discussion in section four, and conclusions in section five.

2 Background

2.1 Definitions

The 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* (Berle et al. 2011b). In maritime supply chain risk management, given a supply chain mission focus, vulnerability is defined as *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* (Berle et al. 2011b), inspired by Asbjørnslett and Rausand (1999).

Risk may be defined according to industry standards, as: *a triplet of scenario, frequency and consequence of events that may contribute negatively* (Kaplan and Garrick 1981). Resilience is *the ability of the supply chain to handle a disruption without significant impact on the ability to serve the supply chain mission*. Resilience is about handling the consequences of a disruption, not about preventing a disruption from occurring. However, the effort to create a resilient system is made before a disruption occurs (Berle et al. 2011b).

2.2. Relevant literature

Supply chain risk management has been a research area of increasing focus within the last ten years, see reviews like Manuj and Mentzer (2008), Juttner (2005) and Vanany et al. (2009). Other relevant research include papers on supply chain disruptions (Chopra and Sodhi 2004; Craighead et al. 2007; Kleindorfer and Saad 2005), supply chain vulnerability (Asbjørnslett 2008; Peck 2005; Wagner and Bode 2006), and supply chain flexibility and resilience (Ponomarov and Holcomb 2009; Tang and Tomlin 2008). More practical approaches towards supply chain risk management can be found in the workbook on supply chain risk by Cranfield University (Cranfield 2003), and in the Supply Chain Council SCOR model on risk management (2009).

Limited previous literature has been found within maritime supply chain risk management. Barnes and Oloruntoba give an overview of risk management from a security perspective (2005), Bichou and Gray (Bichou and Gray 2004) focus on port performance management and the role of ports in supply chains. Carbone and De Martino similarly study the role of ports in maritime supply chains (Carbone and De Martino 2003). Li and Cullinane (LI and Cullinane 2003) assess the economic means ship owners may deploy to reduce their vulnerability towards maritime risks. Panayides (Panayides 2006) bring forth a general discussion on the integration of maritime logistics and global supply chain management, in particular within the container shipping segment. Panayides also suggests an integration of operations research perspectives within maritime logistics in his recommendations for future research, which is a goal of this paper.

Reviews on ship routing problems include Ronen (Ronen 1983, 1993), Christiansen et al. (Christiansen et al. 2004), Brønmo et al. (2007) and Korsvik (2009). Given that a number of decisions have to be made in the presence of uncertainty, where ignoring this may lead to inferior or wrong decisions, it is important to include the modeling of uncertainty in transportation systems (Kleywegt and Shapiro 2001; Ruszczynski and Shapiro 2003). One such way is stochastic optimization, a method that offers a rich modeling approach, but is still under development. However, there is always a “trade-off between the realism of the optimization model (…), and the tractability of the problem”, making it possible to solve (Kleywegt and Shapiro 2001). Recent relevant literature on optimization of LNG shipping problems includes Andersson et al. (2010), describing an inventory management problem of a vertically integrated LNG supply chain, and Rakke et al. (2011), who present a heuristic for creating annual delivery programs with the presence of a spot market.

Monte Carlo methods have been applied on several supply chain problems: You et al (2009) study a chemical supply chain problem, and show how a stochastic model can aid management in reducing financial risk towards variability of customer demand, freight and energy prices. Applequist et al (2000) use Monte Carlo simulations to model the economic risk and rewards to investment in supply chain design and planning projects under uncertainty. Supply chain disruptions were modeled using Monte Carlo and discrete-event simulation by Schmitt and Singh (2009), allowing for testing effects of disruptions and quantifying consequences for a large consumer product company's supply chain.

2.3 Relevant risk assessment methods

Risk analysis approaches may involve both qualitative and quantitative methods. Before commencing, a definition of the system in question and the limits of this system constrain the task at hand to be tangible. In general, as for the Formal Vulnerability Assessment (FVA) (Berle et al. 2011b) framework illustrated in table 1, the hazards to the system should first be described qualitatively to get an overview of the context, both on the cause and consequence sides.

The FVA framework is based on the Formal Safety Assessment framework, used to describe a rational and systematic risk-based approach for safety assessment (IMO 2002; Kristiansen 2005). The adaptation of this framework is described in Berle et al (2011b), arguing that there is much to gain by linking safety and reliability engineering to maritime risk assessment, and for applying FSA beyond vessel risk assessment to understanding vulnerabilities in maritime supply chains.

Initially, qualitative methods give grounds for structuring and describing how the transportation system may break down, while not requiring the resources and much information of the exact characteristics of the hazards and breakdown, typically probability, possible consequences and the impact of these. Typically, a qualitative approach would use checklists, expert judgment and brainstorming.

Later in the process, when the widest possible scope of hazards and potential breakdowns are identified, a selection of the key risks is necessary to limit the task at hand. Semi-quantitative methods draw on quantitative methods, but do not actually use exact numbers for parameters such as probability and consequence. Rather, quantification may be done using scales, e.g. by ranking probability on a scale from one to five. Examples of methods include Preliminary hazard analysis (PHA), Failure Mode, Effect and Criticality Analysis (FMECA) and Hazard and Operability Studies (HAZOP).

Quantitative methods offer the potential to give exact numbers of risk, given that the input data is correct. Examples of quantitative risk assessments include fault and event trees, and approaches such as Quantitative Risk Analysis (QRA) (Vanem et al. 2008). However, obtaining such quantitative data is difficult, in particular for complex systems with limited historical data. For this purpose, quantitative data will be obtained by the use of simulation and operations research methods. Quantitative results from the simulation are returned into the risk models.

Aven et al. (2005; 2007) give an overview holistic approaches to risk research in the offshore industry and how to systematically address this in a structured framework, as do Vatn (2011). Rausand et al.'s textbooks on risk management provide insight into risk management methods (2011; 2004). Some relevant risk assessment methods are presented below:

*Preliminary hazard analysis (*PHA) is an initial semi-quantitative analysis that is intended to identify all potential hazards and accidental events that may lead to an accident (Rausand and Høyland 2004). *Failure Mode, Effect and Criticality Analysis* (FMECA) is a method to determine equipment functions, functional failure modes and possible causes and consequences of such failures (Kristiansen 2005). *Hazard and Operability Studies (*HAZOP) is a detailed and comprehensive hazard identification method, often used in sectors such as process systems and software development (Kristiansen 2005). HAZOP has been applied to supply chain problems by e.g. Adhitya et al. (2009), who compare its use in supply chain to that of a chemical processing plant.

Fault tree analysis (FTA) uses Boolean logic to graphically model logical relationships between equipment failures, human errors and external events that can combine to cause specific mishaps of interest, also called top events (Kristiansen 2005). Event tree analysis (ETA) uses decision trees to model the possible outcomes of an initiating event capable of causing consequences of interest (Kristiansen 2005). Examples of fault and event trees in LNG shipping can be found in Vanem et al. (2008).

2.4 Relevant optimization / planning methods

Most ship routing and scheduling problems can be formulated as mathematical programs which can be solved by using a commercial MP solver. However, due to the complexity of these problems, most real life instances cannot be solved to optimality without spending hours or days. Therefore, heuristic solution methods are often used instead. These methods can provide good (but not necessarily optimal) solutions in reasonable time.

TurboRouter

TurboRouter is a heuristics-based decision support system created by MARINTEK made to aid shipping companies in managing their fleets through solving complex ship routing and scheduling problems (Fagerholt and Lindstad 2007). Presently, this tool is used by a few shipping companies. The essential technology is a multi-start local search heuristic, which is connected to a graphical user interface and an advanced distance calculation module

Invent

Invent is an application developed by SINTEF ICT Applied Mathematics (Kloster 2009). It is a software library for solving maritime inventory problems. This library includes a set of meta-heuristic methods that can be used. The Invent solver can be integrated with TurboRouter through a XML-based interface, and in this way serve as a solver for inventory routing problems modeled in TurboRouter. For this paper, with a huge number of scenarios to solve, keeping the computational time as low as possible is essential. Therefore a constructive heuristic has been chosen in order to solve the scheduling problems. This method provides solutions that are very close to optimality in just a few seconds.

3 Systems definition & simulation setup

Berle et al described the Formal Vulnerability Assessment framework for addressing vulnerability in the ability to move goods of a maritime transportation system (Berle et al.

2011b). This paper presents connecting this risk-related method to planning tools. Being a conceptual paper, this is a simplification, although the general lines are followed.

In short, the FVA adaptation of the safety-oriented Formal Safety Assessment framework is used to understand how maritime transportation systems may break down, the consequences if this happens, and how the transportation system may prepare to restore itself after a disruption has occurred. To facilitate credible cost-efficiency estimation, some quantitative results are needed. On the other hand, this paper is intended as an example of how to perform a vulnerability assessment, not as a full assessment. Thereby, a selection of tasks will be performed for each of the steps in the FVA assessment, as illustrated in table 1. The approach is split into two parts; traditional risk assessment approaches focusing on "what may go wrong" (the hazard focus), and a mission centric path, where the critical capabilities of the system are considered. The latter ensures that unforeseen risks and low-frequency high-impact risks are explicitly included.

Insert Table 1 about here

Table 1: Outline of the FVA process (Berle et al. 2011b)

	Hazard focus	Mission focus
Step 0: Preparation	0: Define system, parameters, criteria, borders etc	
Step 1: Hazard identification	1a: What may go wrong	1b: Which functions / capabilities should be protected
Step 2: Vulnerability assessment	2a: Investigation / quantification, most important risks	2b: Investigation / quantification, all relevant failure modes
Step 3: Vulnerability mitigation	3a: Measures to mitigate most important risks	3b: Measures to restore functions / capabilities
Step 4: Cost / benefit assessment	4a: Cost / benefit assessment	4b: Cost / benefit assessment
Step 5: Recommendations for decision making	5: Recommendation and feedback to assessment	

3.1 System definition

An LNG transportation system can be described through the components as in table 2. The system borders are defined to be from the LNG export harbor storage tanks to the LNG import harbor import tanks. This is due to that the set goals on the supply and demand sides, as can be seen in table 2: The liquefaction plant should ideally be run at 100 % capacity to maximize profits. Likewise, end users demand that their gas needs are met, requiring steady deliveries. Optimization on the system is therefore done given that the export port storage should never run full, and that the import harbors never should run empty. Risk acceptance criteria set limits of how much vulnerability should be accepted, measured in either economic loss, time or volume unavailability.

Insert Table 2 about here

Table 2: Components of the LNG chain (Berle et al. 2011b)

Components	Description	Characteristics	Goals/challenges
Feed gas	Natural gas from fields	Transported in pipelines	Steady usage
Liquefaction plant	Cleans and cools gas to liquid state at – 161°C	High investment and operational cost	Maximize utilization without interruption
Export LNG storage	Storage of LNG before loading	High investment cost	Minimize required capacity

Loading	Moving LNG to ship	Specialized infrastructure	Safe loading, maximize throughput capacity
Port/ship interface	Scheduling and coordination of vessels	Vessels serve as storage in system	Need for frequent loading, long planning horizon, maximize utilization
Shipping network	Owned, chartered (and spot) vessels	Decisions on utilization of owned and chartered fleet	Maximize profits, recourse action for deviation management
Port/ship interface	Scheduling and coordination of vessels	Planned delivery of gas	Limited capacity, long planning horizon, maximize capacity utilization
Unloading	Moving LNG from ship	Specialized infrastructure	Safe unloading, maximize throughput capacity
Import LNG storage	Storage of LNG	High investment cost	Minimize capacity requirement
Regasification	Evaporating LNG to natural gas	Moderate investment	Meet gas demand without interruption
Gas consumption / gas storage	Use of gas, gas to transportation system, gas to storage	Variability in demand with stochastic uncertainty	Meet gas need

3.2 Hazard identification

The hazard identification stage encompasses methods such as PHA, literature surveys, accident databases, checklists and structured brainstorming by experts to identify a wide scope of potential risks. Besides the focus on the functions and capabilities the system is reliant on, the approach is analogous to previous supply chain risk assessment frameworks such as by Manuj and Mentzer (2008).

3.3 Vulnerability assessment and quantification

A foundation for doing credible cost-efficiency tradeoffs is the ability to quantify risk. Given that risk can be defined as a combination of scenario, probability and consequence, in particular the latter are relevant to quantify. However, quantifying risk is notoriously hard to do, due to a set of reasons: First, lack of historical data is relevant, as one cannot easily learn from the past. Supply chain risk management does not allow for experimenting in the closed confines of a laboratory. This sets the potential for experiments apart from for instance risk assessments in technical systems, where a mechanical part can be stressed over time under observation. Second; transportation systems are characterized by tight coupling between the components. Combined with high and increasingly intractable interaction between components, as argued by Perrow (1984), is a recipe for breakdown. Third, the number of potential threats that may cause a disruption is immense. Combining this with limited oversight of the interactions and couplings of the transportation systems leaves putting exact numbers to the scenarios at hand at best as difficult.

“Expert judgment” is used as initial quantification of technical risk assessments of scenarios characterized by one or more of the three factors above. In essence, someone with above average insight into the problem make their best guesses on what the occurrence rate or possible consequence of a disruption would be – a version is to average the numbers found by several experts. Such assessments can be helped by structured techniques, but in essence they are subjective. On the other side, “in the land of the blind, the one-eyed man is king”: an estimate may be better than no information, as long as it does not lead one into a false sense of knowledge.

The presented approach uses simulation to quantify the effects of disruptive events and mitigating measures, as discussed in section 2.3. Quantitative data can then be fed back into the assessment for more precise cost benefit assessments and ultimately better informed decisions.

3.4 Risk mitigation

For a supply chain problem, mitigating vulnerability can in essence be done through two strategies; robustness and flexibility (Sheffi 2005b). Robustness is about having excess resources (such as transportation capacity) to withstand threats, flexibility is about having the ability to reconfigure the resources. In supply chain terminology: what are the bottlenecks of the transportation system? More general; what are the critical functions that the transportation system is dependent on? For identified relevant risks, mitigating measures can be considered. However, the cost/benefit assessment that follows in the next step is necessary to determine whether the measures are worthwhile.

3.5 Cost benefit assessment

To which extent should transportation systems have the ability to withstand threats, and how fast should transport capacity be restored, given that a cost is incurred to give the system such abilities? There is also a cost to having time delays in restoration. However, this balance and cost/efficiency trade-off is not trivial.

We argue that in a cost-benefit assessment of mitigating measures, one should compare the vulnerability reduction gained from each measure with the cost of implementation, using e.g. a net present value [NPV] criteria (Saleh and Marais 2006). Benefits include reduced number of disruptions, reduced impact from each disruption, and increased availability of assets. Costs include investment, operation and training expenditures. Tang (2006) argues that the lack of efforts towards investing in reducing supply chain vulnerability is due to that no-one gets credit for an event that did not occur. Being able to quantify the cost of disruptions and effectiveness of mitigating measures is the reason of existence for this conceptual framework.

3.6 Recommendations for decision making

The Formal Vulnerability Assessment framework suggests that an objective comparison of the identified options should be made based on potential reduction of vulnerability, both to frequent and infrequent risk. The recommendations for decision making should be a synthesis of the formal process, selecting which measures to include based on which are the most critical.

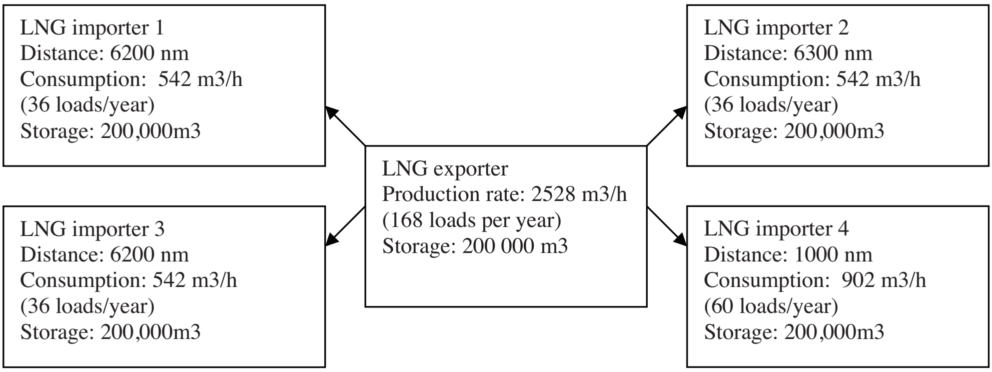
4 Case – Energy security in LNG supply chains

4.1 Case description

The current LNG transportation system may be described as in figure 1. This is based on a real case, although with changes to anonymize the facility and to simplify the assessment, as well as to preserve confidentiality clauses with industry partners. A single export port serves a number of customers, at any time serving a fleet of 10 vessels on long-term contracts. Due to high capital investments in the liquefaction plant, a goal of operation is to minimize down time; the goal of the transportation planning system is to never require the LNG liquefaction plant to reduce production. Limited on-shore LNG storage facilities, about 72 hours of production time from empty to full, require vessels to be available to load regularly.

According to industry sources, about 85% of volumes of the LNG productions are delivered to long-term (over 4 years) contract customers. About 15 % of volumes are sold on the spot market. What is referred to as a spot market in LNG trades are in fact 0.5 – 4 year contracts. Single journey trades, as for instance the typical spot trade in tramp trades, are almost non-existent due to lack of available cargo; this is rather done as rerouting of an already planned journey. To simplify, this model does not include a spot market. Vessels always load full cargoes, serve only one port, and there are no partial discharges.

Figure 1: The transportation system



Several simplifications have been made to this conceptual model. All vessels are considered to be identical with 130,000m3 cargo carrying capacity and a service speed of 18 knots, so one ship can replace another. Cargo types are reduced into only one cargo grade (no rich or lean gas). Customers are considered identical, that is; the only parameters are distances from export port, consumption volumes and cargo storage. Customer may have different LNG volume needs and storage capabilities. Demand is steady, unlike real markets: Normally, summer and winter demands for natural gas is higher in summer and winter than in the spring and fall, as the gas is used for heating and electricity generation (used in air conditioning). There are no seasonal sailing constraints in this model, in real-life applications one would have to consider that winter storms may require vessels to reduce speeds and leave in appropriate buffers for such. Navigational channels etc. are not considered as potential sources of disruption in transit (such as missing a Suez convoy, causing a layover),

Disregarding the simplifications, this is still a complex system, and serves to illustrate the approach towards risk management of maritime transportation systems. For more thorough descriptions of real cases with actual operational constraints, readers are advised to study e.g. Andersson et al. (2010) and Rakke et al. (2011).

An initial constraint introduced in the model reflecting on experts' description on how transportation system routing is performed today, was that vessels had restrictions on which ports that could be served; vessels were dedicated to certain ports. A general comment is that existent vessel planning is done with a large number of additional constraints introduced, such as which vessels can serve which customers, equal usage of one or more vessels, tight delivery windows, low flexibility in re-routing vessels et cetera. In other words, a number of constraints are introduced on the optimization problem without a thorough review of additional costs introduced to the system. The result is sub-optimization towards a large number of individual goals rather that the system as a whole.

4.2 Identified risks: expert judgment

In collaboration with experts, the scenarios presented in table 4 were selected as the most critical, using a-priori (prior) estimates of both probabilities and consequences. The experts are practitioners from the LNG industry representing several stages in the value chain as well as operational fleet planning practitioners, to encompass the scope of LNG supply chain vulnerability in the widest sense. The probabilities for these scenarios occurring were assigned in collaboration with experts, the consequences were determined through the simulation.

Table 4: Generated disruption scenarios for simulation

Generated scenarios:	Description	Probability per day
Production	LNG Production capacity is down 50 % for 48 hours	0.01
Loading port	Loading port is completely unavailable for 48 hours	0.002
Discharge port	One discharge port is completely unavailable for 96 hours	0.002
Tank capacity	Loading port storage tank capacity is down to 24 hour production for 7 days	0.005
Loading rates	Loading rates is down 50% for 7 days	0.001
Berth availability – loading?	Only 4 of 6 loading berths are available for 5 days	0.005
Unloading rates	Unloading rate in one port down 50% for 14 days	0.001
Berth availability – unloading?	Only 1 of 2 unloading berths are available for 14 days	0.001
Extra-ordinary dry-dock schedule	Maintenance need removes 1 vessel for 14 days outside of schedule, plus the vessel needs to be repositioned to the Far East for a suitable yard	0.005

As this is a conceptual paper, we limit our choice of disruption scenarios to four: 1) Production being down 50% for 48 hours, 2) Loading port being completely unavailable for 48 hours, 3) One discharge port being closed for 96 hours, 4) Vessel needing unexpected repair at Far East yard for 14 days, plus repositioning.

4.3 Mitigating measures:

Potential mitigating measures were identified in collaboration with experts to illustrate the approach. These were, including an estimation of costs:

1) Investing in 400,000 m^3 additional LNG storage at the export port. Investment costs would be in the magnitude of USD 125 million, operational expenses about USD 2m/year. Assuming that the investment has to be written off in ten years and a weighted average cost of capital (WACC) of 8%, operational expenses included, the annual cost is about USD 16.5m.
2) Introducing additional storage at import port – either at two or at four of the ports. We estimate that the investment and operational costs would be comparable to that of the export port, i.e. USD 67.5m or USD 125m, and total operational expenses of USD 1m or USD 2m, respectively, resulting in annualized cost of USD8.25m or USD16.5m.
3) Introducing additional vessels as a robust buffer. Renting one 130,000 m3 LNG vessel cost about USD 80,000/day in the current market on a 10 year charter. In addition, USD12,000/day in operational expenses (fuel and crewing) must be included. Annual price is then USD 33.6m per vessel.

Our optimization uses a basic setup with 10 vessels and 200,000 m^3 of LNG storage in the ports, referred to as case 0. We test various system setups with adding combinations of mitigating measures one to three, with half or full implementation of Measure 2. Measure 1 adds one vessel to allow for greater flexibility in using the fleet. Measure 2 adds 400,000 m^3 of storage in the export port. Measure 3 is thought of as a robust and flexible system, albeit at a high cost. To estimate the difference, two vessels and 400,000 m^3 of export port storage is added. This leaves four system setups for the optimization.

4.4 Consequence quantification

The simulation is based on annual delivery programs. Scenarios for 1000 simulations, each of one year, are generated with random occurrences of disruptive events based on probabilities as shown in table 4. The number was chosen to get a large dataset to establish confidence intervals, while limiting run-time of the model in the calculation. For each year, a delivery program is generated. In case of disruptive events, re-calculations of the delivery plan are done according to the defined constraints.

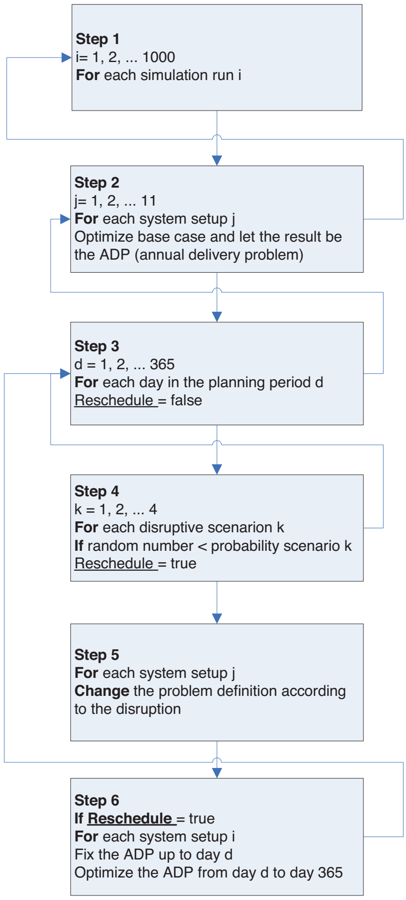
As we have identified a set of mitigating measures, we have 12 potential system setups, as shown in table 5 below. Case 0 is the base case. The 1000 simulations with generated disruptions are run for these 12 system setups.

Table 5: Description of the 12 system setups

Case	Number of vessels	Export port storage	Import port storages
0	10	Low (200,000 m3)	4 low (200,000 m3)
1	10	Low	2 low (200,000 m3), 2 high (300,000 m3)
2	10	Low	4 high (300,000 m3)
3	10	High (600,000 m3)	4 low
4	10	High	2 low, 2 high
5	10	High	4 high
6	11	Low	4 low
7	11	Low	2 low, 2 high
8	11	Low	4 high
9	11	High	4 low
10	11	High	2 low, 2 high
11	11	High	4 high

Goal functions for the optimization can be defined in several ways. The goal of the problem is to maximize delivered quanta of LNG in the system, under storage restrictions. For this problem, the most relevant are optimizing on time-slots or inventory, whereof the last is chosen. Production and consumption rates are assumed constant, storage volumes are fixed, and the goal is to not allow production storage tanks to exceed a loading limit. Similar constraints are set on the import storage tanks. A supplement that was not included is to add an operational limit for tank loading smaller than the physical maximal / minimal volumes. Then, penalty cost for violations of storage limits can be added up to the maximal/minimal storage volumes. The planning problem becomes how to create annual delivery problems for the vessels to ensure that the constraints are not violated, i.e. creating feasible solutions that maximize the annual delivered volume of LNG, while meeting storage requirements.

Figure 2: Flow chart of the simulation



Model: parameters

The system is dimensioned to have ten 130,000 m^3 vessels operating at 18 knots; one vessel, serving the short route to LNG importer 4 (LNGI-4) (6 days per round trip), three to each of the others (30 days per round trip). Resulting LNG consumption rates are 902 m^3/h for LNGI-4, and 542 m^3/h for the others. To balance the system, production must equal consumption, so the LNG export plant produces 2528 m^3/h of LNG. Production storage is set to be 200 000 m3, which is about 79 hours of production, which is a realistic figure. Import storage must be larger than vessel capacity to allow for some flexibility in routing. Also, for import security of supply, larger stores are normally utilized. Import storage is therefore set to 220,000 m^3 for the ports. Loading rates per berth, both for ports and vessels are set to 10,000 m^3/h, which is comparable to existing systems.

Results are measured on two criteria; 1) what is the average delivery potential of the system setup, and 2) what is the downside, i.e. what is the minimal downside we can expect with 95% certainty?

Running a simulation series took ca 42 hours on a computer with a 2.2 Ghz Intel core2 processor with 4 Gb RAM.

4.5 Results

The results are presented as in table 6 and in figure 3.

Table 6: Delivered volumes – average, 95th percentile and "disruption-free"

	Average volume	Deviation: average	95th percentile	Deviation 95th percentile	"Disruption-free" volume	Dev. avg. of max vol.	Dev. 95th. perc. of max. vol.
Case 11	18128760	0,0 %	15730000	-0,8 %	21840000	-17,0 %	-28,0 %
Case 5	18098990	-0,2 %	15860000	0,0 %	21710000	-16,6 %	-26,9 %
Case 4	17865380	-1,5 %	15600000	-1,6 %	21320000	-16,2 %	-26,8 %
Case 10	17852250	-1,5 %	15600000	-1,6 %	21840000	-18,3 %	-28,6 %
Case 8	17670250	-2,5 %	15340000	-3,3 %	21450000	-17,6 %	-28,5 %
Case 3	17659980	-2,6 %	15470000	-2,5 %	21060000	-16,1 %	-26,5 %
Case 9	17647890	-2,7 %	15340000	-3,3 %	21580000	-18,2 %	-28,9 %
Case 7	17500730	-3,5 %	15210000	-4,1 %	21320000	-17,9 %	-28,7 %
Case 6	17311710	-4,5 %	15080000	-4,9 %	21190000	-18,3 %	-28,8 %
Case 2	17164550	-5,3 %	15080000	-4,9 %	21060000	-18,5 %	-28,4 %
Case 1	17061590	-5,9 %	14950000	-5,7 %	20930000	-18,5 %	-28,6 %
Case 0	16930290	-6,6 %	14690000	-7,4 %	20670000	-18,1 %	-28,9 %

What we see above is that the base case (Case 0), the average annual delivered volume is 16.93 million m3 of LNG, with 95% of the certainty that annual delivered volumes will be above 14.69 million m3. The best performing system setups are not surprisingly Cases 5, 10 and 11, namely those with the most mitigating measures added.

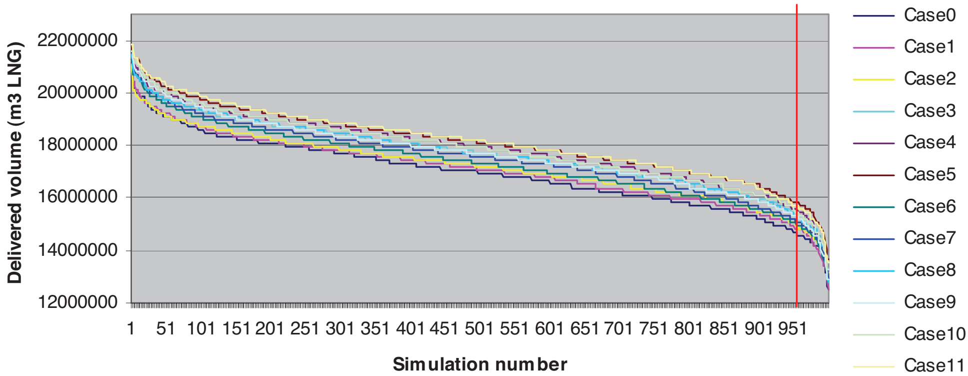
Secondly, we see that comparing where storage should be located, this simulation gives more benefit to adding storage volume at the export port rather than in the import ports, see Case 2 versus Case 3. This difference is evened out with one additional vessel, as can be seen in Case 8 versus Case 9.

On comparing whether to add distributed storage (Measure 2) partially or fully, we see that there is a linear effect of adding volume in Case 1 and 2, where the vessel capacity is limited. When vessel capacity is abundant (Measure 3), there is a diminishing return to adding distributed storage (Case 7 and 8).

The maximal volumes that can be delivered for the various system setups range between 20.67 and 21.84 million m3. This indicates that planning for a system without disruptive events lead to an overestimation of system transportation capacity with c21.4% for the average load and with c39.2% for loads delivered within a 95% confidence interval.

A physical representation of the individual distribution of disruption costs for the 1000 scenarios can be seen below for the four cases. These are sorted in order of declining delivered volumes, to smooth results to allow for illustrating the performance of the system setups. We see is that there are very few cases where delivered volumes are close to the "disruption-free" delivery capacity, i.e. the deterministic volumes. Likewise, figure 3 illustrates that increasing the confidence level of the system from 95% to e.g. 99% or 99.9% decrease the delivered volume disproportionally. This illustrates that a system that can only accept very limited disruptions becomes costly, and that having redundant systems may be more cost-effective than requiring very high operational availability of one single system.

Figure 3: distribution of disruption cost



To challenge our model, we ran the simulation series two more times, with half the probability of disruptions and double the probability of disruptions, respectively. This allows for testing the robustness of our conclusions. In all three simulation runs, case 5 – the setup with additional storage, was preferred. The order of the remaining solutions varies a little, but the general impression is that our analysis is robust.

4.6 Cost benefit analysis

The value of increased robustness in the system is illustrated in figure 3. For a practical case, the cost of adding robustness measures should not exceed the potential value in committing to delivering higher volumes. Assuming an exemplary value of USD 50 per m3 of LNG delivered, and annual costs of the three mitigating measures as described in section 4.3, the resulting system value can be described below. We have used the average value in this example; using the same input parameters, Case 5 is the preferred setup using both average delivered volumes and 95th percentile volumes. The resilience in our system comes from the potential of re-planning the delivery schedule after a disruptive event has occurred.

Our results suggest that the base setup for the transportation system, given our estimates for value of delivered cargo, was inadequate with regards to storage. Adding additional storage to the system, both at the export and import sides, result in higher delivered average volumes in 95% of cases.

Table 7: Cost/efficiency estimates for the 12 system setups

USDm	Value delivered cargo	Additional vessel	Export storage	Import storage	System value
Case 5	904,9		-16,5	-16,5	871,9
Case 4	893,3		-16,5	-8,25	868,5
Case 3	883,0		-16,5		866,5
Case 0	846,5				846,5
Case 1	853,1			-8,25	844,8
Case 2	858,2			-16,5	841,7
Case 11	906,4	-33,6	-16,5	-16,5	839,8
Case 10	892,6	-33,6	-16,5	-8,25	834,3
Case 8	883,5	-33,6		-16,5	833,4
Case 7	875,0	-33,6		-8,25	833,2
Case 9	882,4	-33,6	-16,5		832,3
Case 6	865,6	-33,6			832,0

5 Discussion

In our introduction, we presented two research questions:
RQ1: Can risk assessment methods combined with results from fleet planning provide more insight in creating resilience in maritime supply chains?
RQ2: Does the combination of risk assessment methods and deterministic optimization software provide new insight for a supply chain planning problem under uncertainty?

There are significant difficulties in coping with uncertainties in modeling maritime transportation systems. Stochastic optimization approaches are developing, but do still pose computational challenges and no existing commercial approach has been found that solve a ship scheduling problems. Risk assessment methods combined with deterministic scheduling allows for including uncertainty within supply chain scheduling, as well as to provide quantitative data of system reliability and its costs.

This paper addresses how to systematically address vulnerability in a maritime transportation system using the Formal Vulnerability Assessment approach, how to create quantitative measures of disruption risk and how to test the effect of mitigating measures. These quantitative data are prerequisites for cost efficiency calculations, and may be obtained without requiring excessive resources.

Supply chain simulation using heuristics-based planning tools offers a potential to quantify the impact of disruption scenarios and mitigating measures. This is used to enrich a risk-based approach to the maritime supply chain vulnerability assessment. Monte Carlo simulation is used to simulate a stochastic nature of disruptions, providing a quantification of the system's ability to perform its mission, namely to move goods.

In section four, we have gone through the steps of the Formal Vulnerability Assessment, as illustrated in table 1. As a preparatory exercise, we have defined the system at hand, including the constraints of the system, the parameters in question and that the purpose of the system is to move LNG with minimal disruption to operation, that is to maximize the annual volume of LNG that the maritime supply chain system can transport given disturbing events.

First, we identified what may go wrong, and what the critical functions of the system at hand are. For resource constraints, as well as that the purpose is to illustrate an approach, we have not completed a full hazard identification study and vulnerability assessment. However, with industry experts, we have identified critical risks relevant for this assessment.

Second, we have identified three mitigating measures, based on where we believe the most vulnerable stages of the system is. Our setup allows for testing a number of system setups based on implementation of these mitigating measures. Our results showed that LNG storage facilities, in particular on the export side, provided increased overall delivered volumes for the system. This suggests that the transportation system at hand was set up as "too lean". Anecdotal evidence suggests that this has been the case for several existing LNG supply chains.

Lastly, the cost/efficiency estimation allows for pricing the value of having additional flexibility and robustness into the base case system setup. Flexibility in this case, is the recourse actions provided through the inventory routing and fleet scheduling system, that when a disruption scenario matures the planning system re-plan the fleet schedules to maximize the volume throughput of LNG. For the given parameters, we saw that the high cost of LNG carriers made adding additional tonnage too expensive in all scenarios – the flexibility in being able to move more cargo could not outweigh the cost of hiring in an additional vessel.

The combination of the Formal Vulnerability Assessment framework and using the commercial fleet planning tool TurboRouter with the Invent add-on to facilitate inventory routing, allows for enriching a vulnerability assessment of a transportation system. The Monte Carlo simulation combined with the inventory routing and scheduling tools illustrate how large impact combinations of disruption scenarios can do to a transportation system.

Limitation to this study includes that the assessment was performed on a simplified dataset rather than an existing system. As an illustration of the approach, it serves its mission, although the potential for generalizing the insights is limited.

Statistical analyses on the data material to generalize insights on the severity of the different scenarios are not justified. This is due to that the assessment was performed using a fictive (albeit realistic) scenario with a set of simplifications, that the risk assessment procedures were not comprehensive.

The design of LNG transportation systems are in general made to create lean and cost-efficient systems. However, in this paper we argue that most are created assuming that the world is more stable than what is the case, and that the planning is not considering the energy import dependency of the customers. The consequence is that critical energy transportation infrastructure may be too vulnerable compared to what would be optimal. We believe that the above discussion answers our research questions.

6 **Conclusion**

The presented approach illustrates how risk assessment approaches combined with optimization tools can provide insight into how maritime transportation systems are vulnerable, what the potential consequences there are to such vulnerabilities, and how potential mitigation measures may be assessed.

The World Economic Forum Global Risk Reports (WEF 2008, 2009, 2010) argue that more insight and knowledge on vulnerabilities highly optimized energy supply systems is needed. This paper contribute to this, as practitioners and researchers are given an approach to get more precise quantitative data on disruption costs and cost/efficiency of mitigating measures, providing background data for decisions on investing in reduction of supply chain vulnerability. We argue identifying the “vulnerability inducing bottlenecks” of a transportation systems allows for realizing more robust versions of these systems in a cost-effective manner.

Societies are increasingly becoming more dependent on natural gas as an energy source, where LNG is an enabling technology for both trading and storing this gas. The high cost of infrastructure require high utilization, where optimization tools contribute. All the while, societal demand for high energy supply security requires that gas supply systems are designed to cope with realistic operational conditions, accounting for low-frequency high-impact scenarios. This paper bring these factors together through an approach to analyze and to verify the robustness of energy transportation systems in delivering natural gas.

The presented approach has been demonstrated on a conceptual level in this paper; we argue no material changes is necessary for a larger scale implementation. However, this requires industry involvement and resources on a much larger scale than what has been the scope of this paper.

Future research

An opportunity for future research is to see how stochastic optimization tools can be combined with risk assessment tools to further enrich the understanding of vulnerabilities in sea transportation systems.

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Appendix B: Secondary papers

**SP1: Vulnerability in global natural gas supply chains:
A qualitative assessment of disruption risks in LNG maritime logistics**

BERLE, Ø. and ASBJØRNSLETT, B.E.,
Published: Logistics Research Network Annual Conference 2008. Liverpool, UK.

Abstract
Transportation of Liquefied Natural Gas, LNG, is an industry of considerable growth, and is of increasing relevance to the world energy supplies. Long, complex and tightly integrated value chains may be vulnerable to disruptions, in particular as capacities to offset a sudden lack of ability to deliver goods not necessarily are readily available. This paper discusses consequences and solutions to a low-probability high-impact disruption scenario in the LNG shipping industry, centered on the importance of sea lines of communication. A certification system on disruption risks is suggested as an incentive for stakeholders to assess threats which may interrupt a supply chain one may take part in or depend on. Partaking in any such may bring global benefits as well as being rational to single actors, and may also give a competitive advantage.

SP2: Vulnerability in European natural gas supply chains:
A qualitative assessment of threats and risks in LNG maritime logistics

BERLE, Ø. and ASBJØRNSLETT, B.E.
Published: SAMRISK. 2008: Oslo.

Abstract
The European Union is increasingly dependent on imported natural gas, whereof an increasing share of these imports is liquefied natural gas [LNG]. The LNG trade relies on complex, integrated and tightly engineered supply chains, in which shipping is a significant element.

There is an inherent conflict of interests in the current trade between producers and receivers of LNG, in particular with regards to the optimal trade-off between cost efficiency in production and transportation factors and the robustness and flexibility of the supply chain. As producers govern the investment decision in their own best interest, recipients will have to adapt with measures to better serve their own measure.

Measures to reduce receiving countries vulnerability towards disruption in their natural gas supply are suggested. Sorted by time horizon in which they may be implemented, these measures range from increased global sourcing to military protection of sea lanes, the use of inexpensive excess LNG carriers as seasonal storage, various contractual measures, and construction of new storage facilities.

SP3 Formal Vulnerability Assessment: A methodology for assessing and mitigating strategic vulnerabilities in maritime supply chains

BERLE, Ø. and ASBJØRNSLETT, B.E.
Published: ESREL 2009. Prague, Czech.

Abstract
The Industrialized world, thereby including the European Union, USA, Korea and Japan, is increasingly dependent on imported natural gas, whereof an increasing share of these imports is liquefied natural gas [LNG]. Security of energy supplies is a complex field, involving political, economical and military policies, as well as logistics and supply chain issues, and is of vital interest to all industrialized nations. Both hyper-optimization of logistics chains and energy security were emphasized in the World Economic Forum Global Risks 2008 report [34] as two of four emerging global risks. A structured Formal Vulnerability Assessment methodology is presented, aiming at assessing vulnerabilities in maritime supply chains. Initial insight from case studies in the LNG shipping industry is presented, including system descriptions, hazard identification, and an example of piracy as an unforeseen disruption risk.

SP4: Failure modes in ports – a functional approach to throughput vulnerability

BERLE, Ø., RICE JR, J.B., and ASBJØRNSLETT, B.E.

Published: ESREL. 2010, Taylor&Francis: Rhodes, Greece. p. 190-197.

Abstract

Maritime supply chain risk management is a field of growing interest. Through interviews with maritime transportation industry stakeholders and two surveys, we have observed that while stakeholders in the industry have a solid focus on frequent operational risks, there is a lack of methods for addressing low-frequency high-impact disruption scenarios, in particular in seaports. Keeping a systems perspective, the maritime transportation system is seen as a throughput mechanism. Using the failure mode approach, the key functions and capabilities of the system are identified. To increase the system's resilience, the creation of a "business continuity plan" for each of these failure modes is suggested. This is a powerful approach that allows for handling unforeseen disruptive events by preparing to restore a limited number of critical functions, rather than preparing for hundreds or thousands of potential disruptive events.

Appendix C: Port resilience interviews.

All questions were held with stakeholders within the maritime and port industry. All questions were therefore asked in this context.

Table X: Questions for Port Resilience interviews.

Theme	**Question asked**
Disruptions	Please describe your thoughts on disruptions
	How can supply chains break down?
	Your experiences of supply chain disruptions?
	Experiences of others that you have heard of?
	Previous disasters in your organization?
SCRM planning	What is the state of the art?
	How would you ideally approach the problem?
	Future plans of SCRM planning?
Resilience	What does resilience mean to you?
	How do your organization build in resilience?
	Future plans for resilience?
Methods and approaches	Development of methods and approaches?
	Who's responsible and who should be responsible?
	Updating the assessment? When, routines, comprehensive?
	Background of the methods?
	Your experiences with these methods?
	Organizational involvement around the approach?
	Collaborative versus single person responsible?
	Future plans for methods and approaches?
	Why not more structured methods and approaches?
LFHI-scenarios?	Has LFHI-scenarios been discussed in your organization?
	Do you find it relevant?
Collaboration with others	Do you seek to learn across larger organizations?
	Do you seek to learn from other ports & terminals?
	Do you seek to learn from other fields?
Inspiration	Can you think of other organizations that are forward/thinking with regards to resilience?
	Do you find it feasible for stakeholders in the port- and maritime industry to learn from other fields?
General	Is there anything you want to add?
	Is there anything you want to ask us?

Appendix D: MIT CTL Port Resilience Survey

Questions for the MIT CTL port resilience survey?
Relevant questions from the MIT CTL Global risk survey?

PAGE 1
Researchers at the MIT Center for Transportation and Logistics (CTL) are working to develop ways to make the maritime transportation system - in particular port operations - resilient to disruptions. This survey seeks input from practitioners to help focus and guide our research in this area. It should take about 10 minutes to complete.

Additionally, CTL is part of the Department of Homeland Security (DHS) Center of Excellence that is focused on Port Resilience (Center for Secure and Resilient Ports) and the results of this survey will help advance CTL's efforts in the research initiative.

All responses will be kept confidential and individual responses will not be revealed or shared outside of the research team. All those participating in the survey may receive a copy of a draft paper outlining the initial scan of this issue upon request.

Note that participation is voluntary; you may decline to answer any or all questions, and you may decline further participation, at any time, without adverse consequences.

Thank you in advance for your candid input and feedback. Please contact us directly if you have specific input that the survey does not cover.

Sincerely,
Jim Rice
Deputy Director - MIT Center for Transportation and Logistics
Director - MIT Port Resilience Project
617-258-8584
jrice@mit.edu

P.S. For the purposes of this survey, we consider a disruption to be any time there is a delay to the process and/or flow of materials through the port.

PAGE 2
Q1: What port operations, processes and systems need to be resilient?
(By resilient, we mean being capable of handling disruptions and delays without long term impact on continuing operations and without significant impact on the ability to serve the customer).

Not important	Important but not critical	Critical	Not applicable

Terminal equipment (e.g. cranes, manifolds, piping systems)
Screening/inspection operations
Yard/storage operations (containers, tankage)
Maritime transportation (ship operation, reliability)
Truck/tank loading and unloading operations
Electric utilities
Waterway operation and coordination (availability of tugs, pilots, air draft, etc.)
Communication/Information Systems
Water/waste water systems
Intermodal equipment (e.g. trucks, material handling equipment)
Labor agreements/availability
Gate operations/port entry operations
Berths
Intermodal connections (access to rail and road capacity)

Q2. What are the most important actions that can be taken to reduce the impact of disruptions to ports?

Not important	Important but not critical	Critical

Add terminal capacity - more berths
Add terminal capacity - more equipment (cranes)
Flexible inter-port agreements (between ports)
Flexible intra-port agreements (between parties within the port)
Flexible labor agreements
Reconfigure/improve gate operations
Add equipment - channel clearing
Add equipment - more vessels to coordinate or move vessels
Improve land transportation availability
Improve communications/information systems
Modify waterway coordination systems
Please note any other systems or processes not included in the above list
Modify vessel design
Modify waterways (reconfigure, dredge)
Add utility capacity (electricity, water/waste water systems)
Other (please comment in text box) - Please note any other actions that can reduce the impact of disruptions to ports

PAGE 3 Your Organization

Q3: Please note your headquarters location (if you are a shipper, carrier, third party or freight forwarder) and/or your terminallocations (if you are also a terminal operator or port authority):

	Headquarters Location	Primary Operations Locations
North America		
Central America		
South America		
North Europe		
Eastern Europe		
South Europe		
North Africa		
Africa		
China		
Other Asia Pacific		
Other - If other, please provide additional detail if possible:		

Q4: Please note your role in the maritime transportation system:
Terminal operator
Terminal operator and carrier
Port authority
Port authority and terminal operator
Carrier
Carrier and freight forwarder
Shipper
Shipper and terminal operator
Freight forwarder
Other third party
Please provide additional explanation as needed:

PAGE 4 Waterways

Q5: How frequently have you experienced or observed disruptions in WATERWAY OPERATION in the past 5 years? Please note the source of the disruption.

Weekly	Monthly	Quarterly	Annually	Less frequently than annually	N/A

Labor agreements/availability
Equipment availability (e.g. tugs, other vessels used to coordinate and locally move vessels)
Channel clearing systems and equipment
Waterway monitoring systems (e.g. level, flow, water condition, weather condition)
Waterway access coordination
Electric utilities
Water/waste water systems
Communication/Information Systems
Other (e.g. lock availability; please add comments in text box)

Q6
2. How long were the delays in WATERWAY OPERATIONS? (Please note the average and the longest delay for those disruptions experienced to the best of your memory).

Average delays (in days)	Longest delay (in days)

Labor agreements/availability
Equipment availability (e.g. tugs, other vessels used to coordinate and locally move vessels)
Channel clearing systems and equipment
Waterway monitoring systems (e.g. level, flow, water condition,weather condition)
Waterway access coordination
Electric utilities
Water/waste water systems
Communication/Information Systems
Other (e.g. lock availability; please add comments in text box)

Q7
3. If you are a carrier only, please click below:
Carrier only
Other

PAGE 5 Terminal Operations

Q8: How frequently have you experienced or observed disruptions in TERMINAL OPERATIONS in the past 5 years? Please note the source of the disruption.

Weekly	Monthly	Quarterly	Annually	Less frequently than annually	N/A

Labor agreements/availability
Equipment availability (e.g. cranes, material handling equipment)
Berth availability
Storage availability
Yard/storage operations
Screening/inspection operations
Gate operations
Electric utilities
Water/waste water systems
Communication/Information Systems
Other (e.g. ship delays; please comment in text box below)

Q9: How long were the delays in TERMINAL OPERATIONS? (Please note the average and the longest delay for those disruptions experienced to the best of your memory).

Average delays (in days)	Longest delay (in days)

Labor agreements/availability
Equipment availability (e.g. cranes, material handling equipment)
Berth availability
Storage availability
Average delays (in days) Longest delay (in days)
Yard/storage operations
Screening/inspection operations
Gate operations
Electric utilities
Water/waste water systems
Communication/Information Systems
Other (e.g. ship delays; please comment in text box)

PAGE 6 Intermodal Connections
Q10: How frequently have you experienced or observed disruptions in INTERMODAL CONNECTIONS in the past 5 years? Please note the source of the disruption.

Weekly	Monthly	Quarterly	Annually	Less frequently than annually	N/A

Labor agreements/availability
Equipment availability (e.g. trucks, gate operations, inspection processes)
Truck loading and unloading operations
Rail loading and unloading operations
Roadway capacity
Rail capacity
Gate operation/port entry operations
Electric utilities
Water/waste water systems
Communication/Information Systems
Other (comments in text box)

Q11: How long were the delays in INTERMODAL CONNECTIONS? (Please note the average and the longest delay for those disruptions experienced to the best of your memory).

Average delays (in days)	Longest delay (in days)

Labor agreements/availability
Equipment availability (e.g. trucks, gate operations, inspection processes)
Truck loading and unloading operations
Rail loading and unloading operations
Roadway capacity
Rail capacity
Gate operation/port entry operations
Electric utilities
Water/waste water systems
Communication/Information Systems
Other (comments in text box)

PAGE 7. Impact of Regulation

Q12: To what extent do government agencies' (at all levels) policies and enforcement impact the delays in ports?

No impact	Slight impact	Moderate impact	Significant impact	Not applicable/not familiar with this regulation

Jones Act
96 Hour Advanced Notice of Arrival
Hours of Service Rules
Vessel Inspections
Visa requirements for crew members
10+2 Importer Security Filing requirements
Cargo inspections (CBP, FDA, USDA, ATF, FW, etc.)
Petro-chemical shipping requirements

Q13
2. In your opinion, what regulations make ports - the terminals, intermodal connections, and waterways - more resilient?
(Fill in comments in text box)

Q14
3. In your opinion, what regulations make ports - the terminals, intermodal connections, and waterways - less resilient?
(Fill in comments in text box)

PAGE 8 Thank you

Thank you for your time and input on this study.
Please indicate if you would like to receive a copy of the study results.

Q15: Would you like to receive a copy of the study results?
Yes, I would like to receive a copy of the study results.
No, thanks.

PAGE 9 Request a copy of the study results

Q16: Please note email address
[…]

Q17: Please note name and company
[…]

PAGE 10 Finish
The survey is completed, thank you again for your assistance.

Jim Rice
Deputy Director - MIT Center for Transportation and Logistics
Director - MIT Port Resilience Project
617-258-8584
jrice@mit.edu

Appendix E: MIT CTL Global Supply Chain Risk Survey

BCA Working Copy of MIT Global Risk Survey

1. Introduction

MIT is conducting a global survey of experiences and attitudes toward Supply Chain Risks and Risk Management. Please help by adding your insights and experiences to our growing knowledge base on supply chain risks.

The survey is directed toward supply chain, business and financial management professionals in manufacturing, retail and wholesale distribution companies located in many different regions of the world. Our objective is to understand how regional and cultural differences affect how people think about and manage supply chain risks.

The estimated time to complete this survey is: 12 minutes

Your participation is voluntary. You may decline to answer any or all questions. You may exit from the survey, at any time, without adverse consequences. Your responses will be kept confidential and used only for this study. Individual responses will not be made public and only aggregate results will be reported.

You are welcome to receive a summary of the survey findings when the study is completed, and to receive the summary you will need to provide your email address. If you chose to provide your email address you are allowing MIT to both send you a summary of the study findings and to contact you, if needed, to voluntarily clarify or further explain your responses.

Thank you in advance for your participation.

Dr. Bruce Arntzen
MIT Supply Chain Risk Project Team

1. What is your main job function?

- ○ Risk Management or Business Continuity Planning
- ○ Supply Chain, Logistics, or Operations Management
- ○ Sourcing, Purchasing, or Supplier Management
- ○ Financial Management
- ○ General or Administrative Management
- ○ Engineering, Marketing or Sales
- ○ Other

Other (please specify)

BCA Working Copy of MIT Global Risk Survey

2. Opinions about Risks

1. There are two ways to mitigate supply chain risks:

a. Planning and Implementing RISK PREVENTION Measures
b. Planning and Practicing EVENT RESPONSE Measures

How should your company spend its efforts?

	Spend much more effort planning and implementing RISK PREVENTION measures	>>	Devote equal effort to each	>>>>	Spend much more effort planning and practicing EVENT RESPONSE measures
Select a response	○	○	○	○	○

Comments?

2. Where in your company is the best position to do the following:

	Should be directed centrally	Should be mostly directed centrally	Should be mostly directed at each site (locally)	Should be directed at each site (locally)
Planning Risk Prevention Measures	○	○	○	○
Implementing Risk Prevention Measures	○	○	○	○
Planning Event Response Actions	○	○	○	○
Performing Event Response Actions	○	○	○	○

Comments?

BCA Working Copy of MIT Global Risk Survey

3. How closely does your company share the same sense of urgency around on-time delivery with:

- your most important suppliers?
- your most important customers?

	Different Sense of Urgency	>>	>>>	>>>>	Same Sense of Urgency
How well do your suppliers' share your company's sense of urgency for on-time delivery?	○	○	○	○	○
How well does your company share the same sense of urgency around on-time delivery as your customers?	○	○	○	○	○

Other (please specify)

BCA Working Copy of MIT Global Risk Survey

3. Supply Chain Risks

1. INTERNAL EVENTS

How often has your supply chain (at your site) been disrupted by these events?

Consider only MAJOR disruptions.

	Never	Rarely	About Yearly	Weekly or Monthly	Almost Daily	N/A
Spike in energy costs	○	○	○	○	○	○
Inventory write-off due to new design change	○	○	○	○	○	○
Cash crisis due to customers delaying payment	○	○	○	○	○	○
Price collapse due to a new competitor	○	○	○	○	○	○
Sales collapse due to a new competing product	○	○	○	○	○	○
Cash crisis due to sudden drop in credit rating	○	○	○	○	○	○
Spike in raw material costs	○	○	○	○	○	○
Raw Material supplier failure	○	○	○	○	○	○
Finished Goods manufacturing failure	○	○	○	○	○	○
Transportation carrier failure	○	○	○	○	○	○
Product Quality Failure	○	○	○	○	○	○
Failure of major software systems	○	○	○	○	○	○
Employee theft and executive misdeeds	○	○	○	○	○	○
Other (list below)	○	○	○	○	○	○

Other Supply Chain Risks (please specify)

BCA Working Copy of MIT Global Risk Survey

4. Failure Modes

1. How frequently have you experienced the following types of supply chain disruption?

Consider MAJOR disruptions only.

	Never	Rarely	About yearly	Weekly or monthly	Almost daily	Not Applicable
Your own internal operations are interrupted (e.g. power failure, machine breakdown, fire, etc.)	○	○	○	○	○	○
You cannot communicate with vendors, customers, or other sites (e.g. systems fail, internet down, etc.)	○	○	○	○	○	○
You lose supply of quality materials (e.g. supplier fails or cannot deliver, bad product quality, etc.)	○	○	○	○	○	○
You cannot ship or deliver your products (e.g. no transportation, ports closed, roads blocked, etc.)	○	○	○	○	○	○
Your people are not available (e.g. mass illness, work stoppage, etc.)	○	○	○	○	○	○
You run out of cash (e.g. credit tightens, customer payments late, etc.)	○	○	○	○	○	○
Sudden drop in customer demand (e.g. new competitor, financial crash, etc.)	○	○	○	○	○	○

Other (please specify)

2. What types of disruptions are the most important for your company at your site to be prepared for?

	Types of Supply Chain Disruptions to be Prepared for:
1st most important	
2nd most important	
3rd most important	

Other (please specify)

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5. Supply Chain Risk Management

1. Tell us about Supply Chain Risk Management at your company:

	Yes and it is effective	Yes but it is not very effective	No	I do not know	Not Applicable
We have a "Risk" manager or group	○	○	○	○	○
We have a "Business Continuity" manager or group	○	○	○	○	○
We have a Business Continuity Plan	○	○	○	○	○
We actively work on supply chain risk management	○	○	○	○	○
Our risk manager goes beyond just buying insurance to work on supply chain risk issues	○	○	○	○	○
We work with customers on supply chain risk management	○	○	○	○	○
We work with suppliers on supply chain risk management	○	○	○	○	○
We have a formal security strategy	○	○	○	○	○
We monitor world events for incidents that affect us	○	○	○	○	○
We have an emergency operations center	○	○	○	○	○
We work with law enforcement and emergency management authorities on risk management	○	○	○	○	○
We simulate different supply chain risks and disruptions	○	○	○	○	○
We analyze incidents to identify process improvements	○	○	○	○	○

Comments?

2. Which supply chain risks do you think are UNIQUE or MORE PREVALENT in your region than in other parts of the world?

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6. Background Information

We would like to get some basic information so that we can compare the responses across the participants.

1. Tell us about yourself:

	Age	Gender	Education	Primary Field of Study
Age, Gender, Education, Nationality				

2. What countries and settings have you lived in and worked in?

	Country you grew up in?	Setting where you grew up?	Country you work in now?	Setting where you work now?
Countries & settings				

3. What languages do you speak?

	Primary language spoken as a child	Primary language spoken at work	Secondary language spoken at work
Languages spoken			

4. What industry is your company in?

	What Industry?
Industry	

Other industry (please specify)

5. Tell us about your company:

	Size of Annual Revenues (Globally) in USD	Number of people at your site?	Number of people worldwide?
Your company			

6. Tell us about your job (please select the closest match):

	How long have you worked for this company?	What is your job level?	What function are you in?	How long have you worked in this industry?	How long have you worked in this function?
Job and supply chain position					

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7. See the study results

1. If you are interested in receiving a summary of the results, then please provide us your email address below.

We plan on sending these out in early 2010. This is voluntary and all email addresses will be kept confidential and only used in relation to this survey. By providing your email address you are allowing MIT to both send you a summary of the survey results and to contact you, if needed, to voluntarily clarify or further explain your survey responses. Your email address will not be given to anyone outside of this study.

Email address:

2. Thank you for participating in the Global Risk Survey.

Your responses will be combined with those of other participants around the world to better understand supply chain risk attitudes and experiences.

If you want to contact our research staff, learn more, or get involved in the MIT Global SCALE Risk initiatives then make sure you have provided your email (above) and check the boxes below.

- Contact the researchers
- Learn more
- Get involved

You may provide additional comments below:

Appendix F: Copyright forms

Required enclosure when requesting that a thesis be considered for a doctoral degree

Co-author declaration

Describing the independent research contribution of the candidate and each co-author

This declaration should describe the independent research contribution of both the candidate and each of the co-authors for each paper constituting the thesis.

For each article the declaration should be completed (capital letters if handwritten) and signed by the candidate and the co-author(s). Use the back of the page and/or additional form(s) if necessary.

Article no.: 1

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

Candidate: Øyvind Berle

First author X	Shared first authorship	Second author	Senior author	Other

The independent contribution of the candidate:
I wrote this paper in its entirety, based on secondary paper 4. The approach was based on previous research at MIT, although the expansion into the maritime domain was a novel approach. The concept was refined through discussions with Rice and Asbjørnslett. I took part in all interviews, except from four due to US Security rules and regulations. The questions for the 16 interviews done at MIT were developed in collaboration with Rice, the remainder by the author alone. The surveys were not my work, although I took part in the last stages of formulating questions for the MIT CTL Port Resilience Survey.

Co-author: James B. Rice

First author	Shared first authorship	Second author X	Senior author	Other

Co-author's contribution:
Rice managed the MIT CTL Port Resilience Survey, took initiative to and led the 16 interviews with terminal operators, port authorities and coast guard in the US and Panama. Discussed the concepts and arguments with the author.

Co-author: Bjørn E. Asbjørnslett

First author	Shared first authorship	Second author	Senior author X	Other

Co-author's contribution:
Supervised the paper, discussed the concepts and arguments with the author. Introduced the candidate to the problem.

To the best of your knowledge, has this article been part of a previously evaluated doctoral degree thesis? N

If yes, please elaborate:

....
Signature of candidate

.... Signature of co-author

.... Signature of co-author

.... Signature of co-author

Required enclosure when requesting that a thesis be considered for a doctoral degree

Co-author declaration

Describing the independent research contribution of the candidate and each co-author

This declaration should describe the independent research contribution of both the candidate and each of the co-authors for each paper constituting the thesis.

For each article the declaration should be completed (capital letters if handwritten) and signed by the candidate and the co-author(s). Use the back of the page and/or additional form(s) if necessary.

Article no.: 2

Title: Formal Vulnerability Assessment of a maritime transportation system

Candidate: Øyvind Berle

First author X	Shared first authorship	Second author	Senior author	Other

The independent contribution of the candidate:
I wrote the entire paper, while concepts and arguments were developed together with and discussed with Asbjørnslett and Rice throughout the process. As for paper 1, I took part in all interviews, except from four due to US Security concerns. The questions for the 16 interviews done at MIT were developed in collaboration with Rice, the remainder by the author alone, under supervision by Asbjørnslett. I took part in all interviews, except from four due to US Security rules and regulations. The surveys were not my work, although I took part in the last stages of formulating questions for the MIT CTL Port Resilience Survey.

Co-author: Bjørn E. Asbjørnslett

First author	Shared first authorship	Second author X	Senior author	Other

Co-author's contribution:
Proposed the concept to the first author, supervised the paper, developed and discussed the concepts and arguments with the first author. Introduced the candidate to approaches for vulnerability assessments in a structured manner.

Co-author: James B. Rice

First author	Shared first authorship	Second author	Senior author X	Other

Co-author's contribution:
Rice managed the MIT CTL Port Resilience Survey, took initiative to and led the 16 interviews with terminal operators, port authorities and coast guard in the US and Panama. Discussed the concepts and arguments with the author.

To the best of your knowledge, has this article been part of a previously evaluated doctoral degree thesis? N

If yes, please elaborate:

....
Signature of candidate

.... Signature of co-author

.... Signature of co-author

.... Signature of co-author

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Co-author declaration

Describing the independent research contribution of the candidate and each co-author

This declaration should describe the independent research contribution of both the candidate and each of the co-authors for each paper constituting the thesis.

For each article the declaration should be completed (capital letters if handwritten) and signed by the candidate and the co-author(s). Use the back of the page and/or additional form(s) if necessary.

Article no.: 3

Title: The role of maritime transportation in humanitarian logistics

Candidate: Øyvind Berle

First author X	Shared first authorship	Second author	Senior author	Other

The independent contribution of the candidate:
This paper is the result of a collaboration with Spens, with whom the author started to develop the idea at MIT. The introduction and background is a result of several iterations, where the writing has been shared about equal. The approach and conclusions (sections 3-5) were developed in collaboration with Asbjørnslett and written by the author under supervision by Asbjørnslett.

Co-author: Karen Spens

First author	Shared first authorship	Second author X	Senior author	Other

Co-author's contribution:
Initiated the paper, discussed the concepts and arguments with the author. Wrote about half of the introduction and background parts, focusing on the humanitarian logistics segments.

Co-author: Bjørn E. Asbjørnslett

First author	Shared first authorship	Second author	Senior author X	Other

Co-author's contribution:
Supervised the paper, with substantial input to concept development, and discussed the approaches and arguments with the author.

To the best of your knowledge, has this article been part of a previously evaluated doctoral degree thesis? N

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....
Signature of candidate

.... Signature of co-author
Karen Spens

.... Signature of co-author

.... Signature of co-author

Required enclosure when requesting that a thesis be considered for a doctoral degree

Co-author declaration

Describing the independent research contribution of the candidate and each co-author

This declaration should describe the independent research contribution of both the candidate and each of the co-authors for each paper constituting the thesis.

For each article the declaration should be completed (capital letters if handwritten) and signed by the candidate and the co-author(s). Use the back of the page and/or additional form(s) if necessary.

Article no.: 4

Title: Optimization, risk assessment and resilience in LNG transportation systems

Candidate: Øyvind Berle

First author X	Shared first authorship	Second author	Senior author	Other

The independent contribution of the candidate:
The paper was written in its entirety by the author (except from the part about optimization tools). The concept was developed in collaboration with Asbjørnslett, the risk assessment and simulation approach by the author alone. Simulation model development was performed in collaboration with Norstad, who made the interface between the risk assessment and simulation tool. The author did all simulations, including setups, and performed data analysis on the results.

Co-author: Inge Norstad

First author	Shared first authorship	Second author X	Senior author	Other

Co-author's contribution:
Developed the simulation model. Programmed the risk assessment approach into the simulation model. Reviewed and discussed the results, and the presentation of the results. Wrote section 2.4, formulated figure 2.

Co-author: Bjørn E. Asbjørnslett

First author	Shared first authorship	Second author	Senior author X	Other

Co-author's contribution:
Supervised the paper, developed the concept in collaboration with the first author, and discussed the approach and arguments with the author.

To the best of your knowledge, has this article been part of a previously evaluated doctoral degree thesis? N

If yes, please elaborate:

Øyvind Berle
....
Signature of candidate

Inge
....
Signature of co-author

....
Signature of co-author

....
Signature of co-author

Appendix G: Theses at NTNU

Report No.	Author	Title
	Kavlie, Dag	Optimization of Plane Elastic Grillages, 1967
	Hansen, Hans R.	Man-Machine Communication and Data-Storage Methods in Ship Structural Design, 1971
	Gisvold, Kaare M.	A Method for non-linear mixed -integer programming and its Application to Design Problems, 1971
	Lund, Sverre	Tanker Frame Optimalization by means of SUMT-Transformation and Behaviour Models, 1971
	Vinje, Tor	On Vibration of Spherical Shells Interacting with Fluid, 1972
	Lorentz, Jan D.	Tank Arrangement for Crude Oil Carriers in Accordance with the new Anti-Pollution Regulations, 1975
	Carlsen, Carl A.	Computer-Aided Design of Tanker Structures, 1975
	Larsen, Carl M.	Static and Dynamic Analysis of Offshore Pipelines during Installation, 1976
UR-79-01	Brigt Hatlestad, MK	The finite element method used in a fatigue evaluation of fixed offshore platforms. (Dr.Ing. Thesis)
UR-79-02	Erik Pettersen, MK	Analysis and design of cellular structures. (Dr.Ing. Thesis)
UR-79-03	Sverre Valsgård, MK	Finite difference and finite element methods applied to nonlinear analysis of plated structures. (Dr.Ing. Thesis)
UR-79-04	Nils T. Nordsve, MK	Finite element collapse analysis of structural members considering imperfections and stresses due to fabrication. (Dr.Ing. Thesis)
UR-79-05	Ivar J. Fylling, MK	Analysis of towline forces in ocean towing systems. (Dr.Ing. Thesis)
UR-80-06	Nils Sandsmark, MM	Analysis of Stationary and Transient Heat Conduction by the Use of the Finite Element Method. (Dr.Ing. Thesis)
UR-80-09	Sverre Haver, MK	Analysis of uncertainties related to the stochastic modeling of ocean waves. (Dr.Ing. Thesis)
UR-81-15	Odland, Jonas	On the Strength of welded Ring stiffened cylindrical Shells primarily subjected to axial Compression
UR-82-17	Engesvik, Knut	Analysis of Uncertainties in the fatigue Capacity of Welded Joints
UR-82-18	Rye, Henrik	Ocean wave groups
UR-83-30	Eide, Oddvar Inge	On Cumulative Fatigue Damage in Steel Welded Joints
UR-83-33	Mo, Olav	Stochastic Time Domain Analysis of Slender Offshore Structures
UR-83-34	Amdahl, Jørgen	Energy absorption in Ship-platform impacts
UR-84-37	Mørch, Morten	Motions and mooring forces of semi submersibles as determined by full-scale measurements and theoretical analysis
UR-84-38	Soares, C. Guedes	Probabilistic models for load effects in ship structures
UR-84-39	Aarsnes, Jan V.	Current forces on ships
UR-84-40	Czujko, Jerzy	Collapse Analysis of Plates subjected to Biaxial Compression and Lateral Load
UR-85-46	Alf G. Engseth, MK	Finite element collapse analysis of tubular steel offshore structures. (Dr.Ing. Thesis)
UR-86-47	Dengody Sheshappa, MP	A Computer Design Model for Optimizing Fishing Vessel Designs Based on Techno-Economic Analysis. (Dr.Ing. Thesis)
UR-86-48	Vidar Aanesland, MH	A Theoretical and Numerical Study of Ship Wave Resistance. (Dr.Ing. Thesis)
UR-86-49	Heinz-Joachim Wessel, MK	Fracture Mechanics Analysis of Crack Growth in Plate Girders. (Dr.Ing. Thesis)
UR-86-50	Jon Taby, MK	Ultimate and Post-ultimate Strength of Dented Tubular Members. (Dr.Ing. Thesis)
UR-86-51	Walter Lian, MH	A Numerical Study of Two-Dimensional Separated Flow Past Bluff Bodies at Moderate KC-Numbers. (Dr.Ing. Thesis)
UR-86-52	Bjørn Sortland, MH	Force Measurements in Oscillating Flow on Ship Sections and Circular Cylinders in a U-Tube Water Tank. (Dr.Ing. Thesis)
UR-86-53	Kurt Strand, MM	A System Dynamic Approach to One-dimensional Fluid Flow. (Dr.Ing. Thesis)
UR-86-54	Arne Edvin Løken, MH	Three Dimensional Second Order Hydrodynamic Effects on Ocean Structures in Waves. (Dr.Ing. Thesis)

UR-86-55	Sigurd Falch, MH	A Numerical Study of Slamming of Two-Dimensional Bodies. (Dr.Ing. Thesis)
UR-87-56	Arne Braathen, MH	Application of a Vortex Tracking Method to the Prediction of Roll Damping of a Two-Dimension Floating Body. (Dr.Ing. Thesis)
UR-87-57	Bernt Leira, MK	Gaussian Vector Processes for Reliability Analysis involving Wave-Induced Load Effects. (Dr.Ing. Thesis)
UR-87-58	Magnus Småvik, MM	Thermal Load and Process Characteristics in a Two-Stroke Diesel Engine with Thermal Barriers (in Norwegian). (Dr.Ing. Thesis)
MTA-88-59	Bernt Arild Bremdal, MP	An Investigation of Marine Installation Processes – A Knowledge - Based Planning Approach. (Dr.Ing. Thesis)
MTA-88-60	Xu Jun, MK	Non-linear Dynamic Analysis of Space-framed Offshore Structures. (Dr.Ing. Thesis)
MTA-89-61	Gang Miao, MH	Hydrodynamic Forces and Dynamic Responses of Circular Cylinders in Wave Zones. (Dr.Ing. Thesis)
MTA-89-62	Martin Greenhow, MH	Linear and Non-Linear Studies of Waves and Floating Bodies. Part I and Part II. (Dr.Techn. Thesis)
MTA-89-63	Chang Li, MH	Force Coefficients of Spheres and Cubes in Oscillatory Flow with and without Current. (Dr.Ing. Thesis
MTA-89-64	Hu Ying, MP	A Study of Marketing and Design in Development of Marine Transport Systems. (Dr.Ing. Thesis)
MTA-89-65	Arild Jæger, MH	Seakeeping, Dynamic Stability and Performance of a Wedge Shaped Planing Hull. (Dr.Ing. Thesis)
MTA-89-66	Chan Siu Hung, MM	The dynamic characteristics of tilting-pad bearings
MTA-89-67	Kim Wikstrøm, MP	Analysis av projekteringen for ett offshore projekt. (Licenciat-avhandling)
MTA-89-68	Jiao Guoyang, MK	Reliability Analysis of Crack Growth under Random Loading, considering Model Updating. (Dr.Ing. Thesis)
MTA-89-69	Arnt Olufsen, MK	Uncertainty and Reliability Analysis of Fixed Offshore Structures. (Dr.Ing. Thesis)
MTA-89-70	Wu Yu-Lin, MR	System Reliability Analyses of Offshore Structures using improved Truss and Beam Models. (Dr.Ing. Thesis)
MTA-90-71	Jan Roger Hoff, MH	Three-dimensional Green function of a vessel with forward speed in waves. (Dr.Ing. Thesis)
MTA-90-72	Rong Zhao, MH	Slow-Drift Motions of a Moored Two-Dimensional Body in Irregular Waves. (Dr.Ing. Thesis)
MTA-90-73	Atle Minsaas, MP	Economical Risk Analysis. (Dr.Ing. Thesis)
MTA-90-74	Knut-Aril Farnes, MK	Long-term Statistics of Response in Non-linear Marine Structures. (Dr.Ing. Thesis)
MTA-90-75	Torbjørn Sotberg, MK	Application of Reliability Methods for Safety Assessment of Submarine Pipelines. (Dr.Ing. Thesis)
MTA-90-76	Zeuthen, Steffen, MP	SEAMAID. A computational model of the design process in a constraint-based logic programming environment. An example from the offshore domain. (Dr.Ing. Thesis)
MTA-91-77	Haagensen, Sven, MM	Fuel Dependant Cyclic Variability in a Spark Ignition Engine - An Optical Approach. (Dr.Ing. Thesis)
MTA-91-78	Løland, Geir, MH	Current forces on and flow through fish farms. (Dr.Ing. Thesis)
MTA-91-79	Hoen, Christopher, MK	System Identification of Structures Excited by Stochastic Load Processes. (Dr.Ing. Thesis)
MTA-91-80	Haugen, Stein, MK	Probabilistic Evaluation of Frequency of Collision between Ships and Offshore Platforms. (Dr.Ing. Thesis)
MTA-91-81	Sødahl, Nils, MK	Methods for Design and Analysis of Flexible Risers. (Dr.Ing. Thesis)
MTA-91-82	Ormberg, Harald, MK	Non-linear Response Analysis of Floating Fish Farm Systems. (Dr.Ing. Thesis)
MTA-91-83	Marley, Mark J., MK	Time Variant Reliability under Fatigue Degradation. (Dr.Ing. Thesis)
MTA-91-84	Krokstad, Jørgen R., MH	Second-order Loads in Multidirectional Seas. (Dr.Ing. Thesis)
MTA-91-85	Molteberg, Gunnar A., MM	The Application of System Identification Techniques to Performance Monitoring of Four Stroke Turbocharged Diesel Engines. (Dr.Ing. Thesis)
MTA-92-86	Mørch, Hans Jørgen Bjelke, MH	Aspects of Hydrofoil Design: with Emphasis on Hydrofoil Interaction in Calm Water. (Dr.Ing. Thesis)

MTA-92-87	Chan Siu Hung, MM	Nonlinear Analysis of Rotordynamic Instabilities in Highspeed Turbomachinery. (Dr.Ing. Thesis)
MTA-92-88	Bessason, Bjarni, MK	Assessment of Earthquake Loading and Response of Seismically Isolated Bridges. (Dr.Ing. Thesis)
MTA-92-89	Langli, Geir, MP	Improving Operational Safety through exploitation of Design Knowledge - an investigation of offshore platform safety. (Dr.Ing. Thesis)
MTA-92-90	Sævik, Svein, MK	On Stresses and Fatigue in Flexible Pipes. (Dr.Ing. Thesis)
MTA-92-91	Ask, Tor Ø., MM	Ignition and Flame Growth in Lean Gas-Air Mixtures. An Experimental Study with a Schlieren System. (Dr.Ing. Thesis)
MTA-86-92	Hessen, Gunnar, MK	Fracture Mechanics Analysis of Stiffened Tubular Members. (Dr.Ing. Thesis)
MTA-93-93	Steinebach, Christian, MM	Knowledge Based Systems for Diagnosis of Rotating Machinery. (Dr.Ing. Thesis)
MTA-93-94	Dalane, Jan Inge, MK	System Reliability in Design and Maintenance of Fixed Offshore Structures. (Dr.Ing. Thesis)
MTA-93-95	Steen, Sverre, MH	Cobblestone Effect on SES. (Dr.Ing. Thesis)
MTA-93-96	Karunakaran, Daniel, MK	Nonlinear Dynamic Response and Reliability Analysis of Drag-dominated Offshore Platforms. (Dr.Ing. Thesis)
MTA-93-97	Hagen, Arnulf, MP	The Framework of a Design Process Language. (Dr.Ing. Thesis)
MTA-93-98	Nordrik, Rune, MM	Investigation of Spark Ignition and Autoignition in Methane and Air Using Computational Fluid Dynamics and Chemical Reaction Kinetics. A Numerical Study of Ignition Processes in Internal Combustion Engines. (Dr.Ing. Thesis)
MTA-94-99	Passano, Elizabeth, MK	Efficient Analysis of Nonlinear Slender Marine Structures. (Dr.Ing. Thesis)
MTA-94-100	Kvålsvold, Jan, MH	Hydroelastic Modelling of Wetdeck Slamming on Multihull Vessels. (Dr.Ing. Thesis)
MTA-94-102	Bech, Sidsel M., MK	Experimental and Numerical Determination of Stiffness and Strength of GRP/PVC Sandwich Structures. (Dr.Ing. Thesis)
MTA-95-103	Paulsen, Hallvard, MM	A Study of Transient Jet and Spray using a Schlieren Method and Digital Image Processing. (Dr.Ing. Thesis)
MTA-95-104	Hovde, Geir Olav, MK	Fatigue and Overload Reliability of Offshore Structural Systems, Considering the Effect of Inspection and Repair. (Dr.Ing. Thesis)
MTA-95-105	Wang, Xiaozhi, MK	Reliability Analysis of Production Ships with Emphasis on Load Combination and Ultimate Strength. (Dr.Ing. Thesis)
MTA-95-106	Ulstein, Tore, MH	Nonlinear Effects of a Flexible Stern Seal Bag on Cobblestone Oscillations of an SES. (Dr.Ing. Thesis)
MTA-95-107	Solaas, Frøydis, MH	Analytical and Numerical Studies of Sloshing in Tanks. (Dr.Ing. Thesis)
MTA-95-108	Hellan, Øyvind, MK	Nonlinear Pushover and Cyclic Analyses in Ultimate Limit State Design and Reassessment of Tubular Steel Offshore Structures. (Dr.Ing. Thesis)
MTA-95-109	Hermundstad, Ole A., MK	Theoretical and Experimental Hydroelastic Analysis of High Speed Vessels. (Dr.Ing. Thesis)
MTA-96-110	Bratland, Anne K., MH	Wave-Current Interaction Effects on Large-Volume Bodies in Water of Finite Depth. (Dr.Ing. Thesis)
MTA-96-111	Herfjord, Kjell, MH	A Study of Two-dimensional Separated Flow by a Combination of the Finite Element Method and Navier-Stokes Equations. (Dr.Ing. Thesis)
MTA-96-112	Æsøy, Vilmar, MM	Hot Surface Assisted Compression Ignition in a Direct Injection Natural Gas Engine. (Dr.Ing. Thesis)
MTA-96-113	Eknes, Monika L., MK	Escalation Scenarios Initiated by Gas Explosions on Offshore Installations. (Dr.Ing. Thesis)
MTA-96-114	Erikstad, Stein O., MP	A Decision Support Model for Preliminary Ship Design. (Dr.Ing. Thesis)
MTA-96-115	Pedersen, Egil, MH	A Nautical Study of Towed Marine Seismic Streamer Cable Configurations. (Dr.Ing. Thesis)
MTA-97-116	Moksnes, Paul O., MM	Modelling Two-Phase Thermo-Fluid Systems Using Bond Graphs. (Dr.Ing. Thesis)

MTA-97-117	Halse, Karl H., MK	On Vortex Shedding and Prediction of Vortex-Induced Vibrations of Circular Cylinders. (Dr.Ing. Thesis)
MTA-97-118	Igland, Ragnar T., MK	Reliability Analysis of Pipelines during Laying, considering Ultimate Strength under Combined Loads. (Dr.Ing. Thesis)
MTA-97-119	Pedersen, Hans-P., MP	Levendefiskteknologi for fiskefartøy. (Dr.Ing. Thesis)
MTA-98-120	Vikestad, Kyrre, MK	Multi-Frequency Response of a Cylinder Subjected to Vortex Shedding and Support Motions. (Dr.Ing. Thesis)
MTA-98-121	Azadi, Mohammad R. E., MK	Analysis of Static and Dynamic Pile-Soil-Jacket Behaviour. (Dr.Ing. Thesis)
MTA-98-122	Ulltang, Terje, MP	A Communication Model for Product Information. (Dr.Ing. Thesis)
MTA-98-123	Torbergsen, Erik, MM	Impeller/Diffuser Interaction Forces in Centrifugal Pumps. (Dr.Ing. Thesis)
MTA-98-124	Hansen, Edmond, MH	A Discrete Element Model to Study Marginal Ice Zone Dynamics and the Behaviour of Vessels Moored in Broken Ice. (Dr.Ing. Thesis)
MTA-98-125	Videiro, Paulo M., MK	Reliability Based Design of Marine Structures. (Dr.Ing. Thesis)
MTA-99-126	Mainçon, Philippe, MK	Fatigue Reliability of Long Welds Application to Titanium Risers. (Dr.Ing. Thesis)
MTA-99-127	Haugen, Elin M., MH	Hydroelastic Analysis of Slamming on Stiffened Plates with Application to Catamaran Wetdecks. (Dr.Ing. Thesis)
MTA-99-128	Langhelle, Nina K., MK	Experimental Validation and Calibration of Nonlinear Finite Element Models for Use in Design of Aluminium Structures Exposed to Fire. (Dr.Ing. Thesis)
MTA-99-129	Berstad, Are J., MK	Calculation of Fatigue Damage in Ship Structures. (Dr.Ing. Thesis)
MTA-99-130	Andersen, Trond M., MM	Short Term Maintenance Planning. (Dr.Ing. Thesis)
MTA-99-131	Tveiten, Bård Wathne, MK	Fatigue Assessment of Welded Aluminium Ship Details. (Dr.Ing. Thesis)
MTA-99-132	Søreide, Fredrik, MP	Applications of underwater technology in deep water archaeology. Principles and practice. (Dr.Ing. Thesis)
MTA-99-133	Tønnessen, Rune, MH	A Finite Element Method Applied to Unsteady Viscous Flow Around 2D Blunt Bodies With Sharp Corners. (Dr.Ing. Thesis)
MTA-99-134	Elvekrok, Dag R., MP	Engineering Integration in Field Development Projects in the Norwegian Oil and Gas Industry. The Supplier Management of Norne. (Dr.Ing. Thesis)
MTA-99-135	Fagerholt, Kjetil, MP	Optimeringsbaserte Metoder for Ruteplanlegging innen skipsfart. (Dr.Ing. Thesis)
MTA-99-136	Bysveen, Marie, MM	Visualization in Two Directions on a Dynamic Combustion Rig for Studies of Fuel Quality. (Dr.Ing. Thesis)
MTA-2000-137	Storteig, Eskild, MM	Dynamic characteristics and leakage performance of liquid annular seals in centrifugal pumps. (Dr.Ing. Thesis)
MTA-2000-138	Sagli, Gro, MK	Model uncertainty and simplified estimates of long term extremes of hull girder loads in ships. (Dr.Ing. Thesis)
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