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.

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). 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.

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). 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.

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 (Kristiansen 2005). 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. (2009), 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 (Kristiansen 2005). 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 (Kristiansen 2005). This modeling technique is applicable for modeling 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. 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.

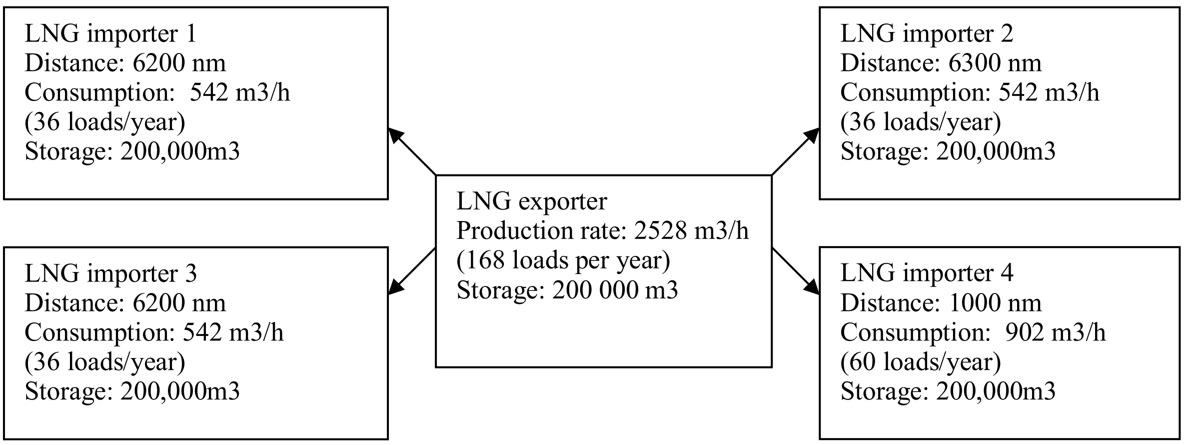
4 Case – Energy security in LNG supply chains

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 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.

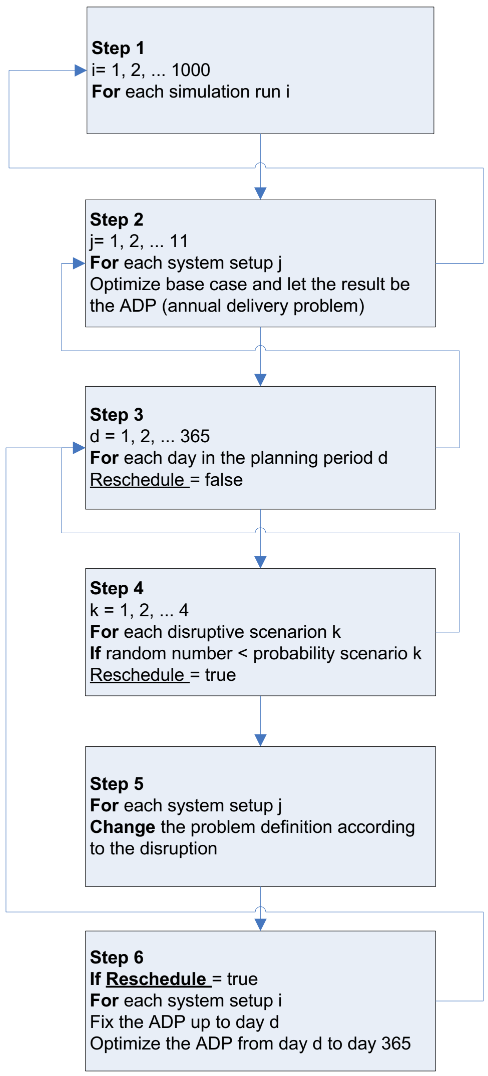
As we have identified a set of mitigating measures, we have 12 potential system setups, as shown in table 5 below. Case 0 is the base case. The 1000 simulations with generated disruptions are run for these 12 system setups.

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.

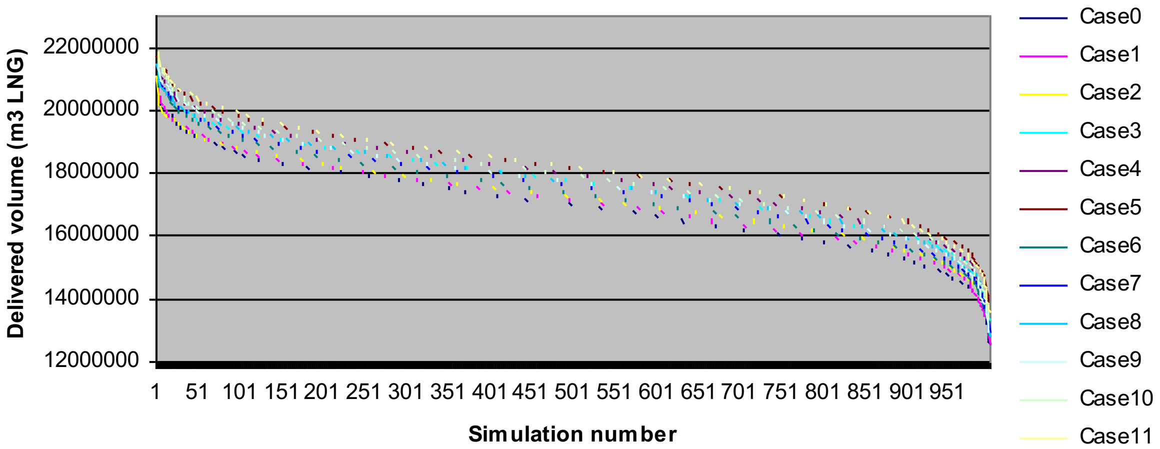


Figure 3: Distribution of disruption cost

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.

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. Identifying the "vulnerability inducing bottlenecks" of a transportation systems, allows for realizing more robust versions of these systems in a cost-effective manner.

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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