Reliability Engineering and System Safety 96 (2011) 696–705

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

Formal Vulnerability Assessment of a maritime transportation system

Øyvind Berle [a,*], Bjørn Egil Asbjørnslett [a], James B. Rice [b]

[a] Norwegian University of Science and Technology, Department of Marine Technology, Trondheim, Norway
[b] Massachusetts Institute of Technology, Center for Transportation and Logistics, Cambridge, USA

ARTICLE INFO

Available online 1 January 2011

Keywords:
Supply chain disruptions
Vulnerability
Failure modes
Maritime transportation
Resilience

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

* Correspondence to: NTNU, IMT, Otto Nielsens vei 10, 7491 Trondheim, Norway. Tel.: +47 40230030.
E-mail address: berle@ntnu.no (Ø. Berle).

0951-8320/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ress.2010.12.011

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.

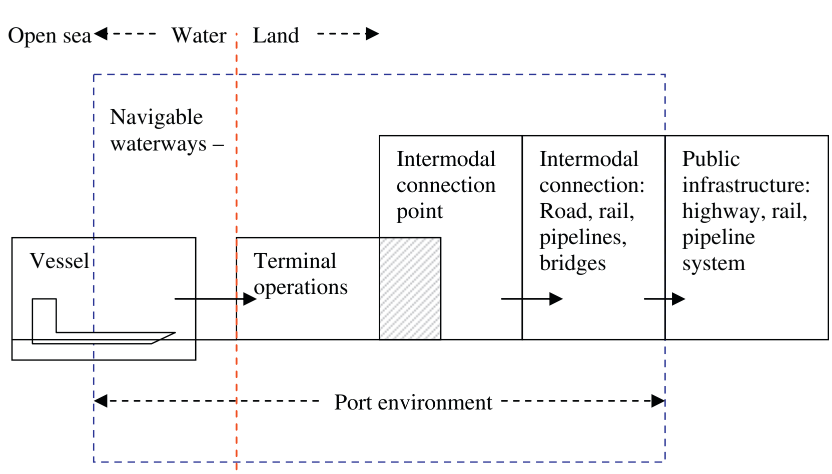

Fig. 1. Sea-land interface of maritime transportation system [4].

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 superstructure	Infrastructure leading to public infrastructure system, supplies for transportation and maintenance	Navigable water	Availability of vessels in market—type, size, features, characteristics
Financial flows	Access to capital, liquidity and revenue to fund operations and expansion of infrastructure	Access to capital, liquidity and revenue to fund operations and investments in superstructure	Revenues, access to capital and liquidity to invest in warehouses, storage yards and connecting infrastructure	Access to capital and investment for dredging, safety measures and expansion	Revenues, access to capital and liquidity, for operating and investing in vessels
Transportation	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.

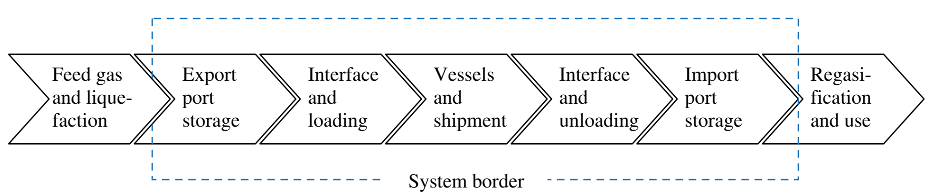

Fig. 2. Components and border of LNG transportation system.

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.

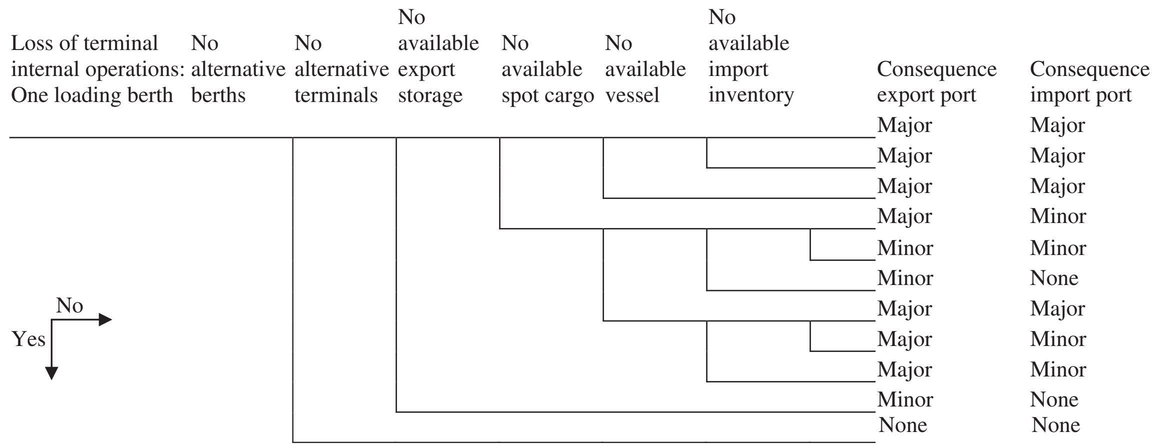

Fig. 3. Event tree for loss of terminal internal operations.

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.

Acknowledgements

We wish to express our sincere gratitude to two anonymous referees for their constructive comments and review, as well as Kai Trepte at the MIT Center for Transportation and Logistics for inputs and comments on earlier versions of this paper. Øyvind Berle would like to express his gratitude to the Norwegian Research Council through the MARRISK research project for financing his doctoral fellowship, along with the Fulbright foundation, the Jansons' fellowship and the DNV fellowship for financial support for his research stay at the MIT Center for Transportation and Logistics.

References

[1] WEF. Global risks 2008—a global risk network report. World Economic Forum; 2008.
[2] Perrow C. Normal accidents. Living with high-risk technologies. New York: Basic Books; 1984.
[3] WEF. Global risks 2009—a global risk network report. World Economic Forum; 2009.
[4] WEF. Global risks 2010—a global risk network report. World Economic Forum; 2010. p. 23.
[5] Womack JP, Jones DT, Roos D. The machine that changed the world : the story of lean production. New York: Harper Perennial; 1991.
[6] UNCTAD. Review of maritime transport. In: Proceedings of the United Nations conference on trade and development. New York, Geneva: 2009.
[7] Kristiansen S. Maritime transportation—safety management and risk analysis. Elsevier Butterworth-Heinemann; 2005.
[8] Rausand M, Høyland A. System reliability theory: models, statistical methods and applications. 2nd ed.. New York: Wiley; 2004.
[9] Asbjørnslett BE, Rausand M. Assess the vulnerability of your production system. Production Planning and Control 1999;10(3):219–29.
[10] Kaplan S, Garrick JB. On the quantitative definition of risk. Risk Analysis 1981;1:1.
[11] Mentzer JT, et al. Defining supply chain management. Journal of Business Logistics 2001;22:2.
[12] Jüttner U, Peck H, Christopher M. Supply chain risk management: outlining an agenda for future research. Internation Journal of Logistics: Research and Applications 2003;6(4):197–210.
[13] Sheffi Y. The resilient enterprise—overcoming vulnerability for competitive advantage. Cambridge: MIT Press; 2005.
[14] Berle Ø, Rice JB Jr, Asbjørnslett BE. Failure modes in ports—a functional approach to throughput vulnerability. In: Proceedings of ESREL. Rhodes, Greece: Taylor & Francis; 2010. p. 190–97.
[15] Rao S, Goldsby TJ. Supply chain risks: a review and typology. The International Journal of Logistics Management 2009;20(1):97–123.
[16] Vanany I, Zailani S, Pujawan N. Supply chain risk management: literature review and future research. International Journal of Information Systems and Supply Chain Management 2009;2:16–33.
[17] Tang CS. Perspectives in supply chain risk management. International Journal of Production Economics 2006;103:451–88.
[18] Kleindorfer PR, Saad GH. Managing disruption risks in supply chains. Production and Operations Management 2005;14(1):53–68.
[19] Zsidisin GA, Melnyk SA, Ragatz GL. An institutional theory perspective of business continuity planning for purchasing and supply management. International Journal of Production Research 2005;43(16):3401–20.
[20] Manuj I, Mentzer JT. Global supply chain risk management. Journal of Business Logistics 2008;29:1.
[21] Carbone V, DE Martino M. The changing role of ports in supply-chain management: an empirical analysis. Maritime Policy and Management 2003; 30(4):305–20.
[22] Bichou K, Gray R. A critical review of conventional terminology for classifying seaports. Transport Research Part A 2005;29:75–92.
[23] De Martino M, Morvillo A. Activities, resources and inter-organizational relationships: key factors in port competitiveness. Maritime Policy and Management 2008;35(6):571–89.
[24] Barnes P, Oloruntoba R. Assurance of security in maritime supply chains: conceptual issues of vulnerability and crisis management. Journal of International Management 2005;11:519–40.
[25] Craighead CW, et al. The severity of supply chain disruptions: design characteristics and mitigation capabilities. Decision Sciences 2007;38(1): 131–56.
[26] Jüttner U. Supply chain risk management: understanding the business requirements from a practitioner perspective. International Journal of Logistics Management 2005;16(1):120.
[27] Rice Jr JB, Caniato F. Building a secure and resilient supply network. Supply Chain Management Review 2003;7(5):22.
[28] Hendricks KB, Singhal VR. An empirical analysis of the effect of supply chain disruptions on long-run stock price performance and equity risk of the firm. Production and Operations Management 2005;14(1):35.
[29] Broadman HG. The social cost of imported oil. Energy Policy 1984;14(3): 242–52.
[30] Korsvik JE. Heuristic solution methods for ship routing and scheduling problems. Trondheim: Department of Marine Technology. Norwegian University of Science and Technology; 2009.
[31] Ronen D. Ship scheduling: the last decade. European Journal of Operational Research 1993;71:325–33.
[32] Ronen D. Cargo ships routing and scheduling: survey of models and problems. European Journal of Operational Research 1983;12:119–26.
[33] Christiansen M, Fagerholt K, RONEN D. Ship routing and scheduling: status and perspectives. Transportation Science 2004;38(1):1–18.
[34] Grønhaug R, Christiansen M. Supply chain optimization for the liquefied natural gas business. In: Bertazzi L, editor. Innovation in Distributions Logistics, 2009.
[35] Chang SE. Disasters and transport systems: loss, recovery and competition at the Port of Kobe after the 1995 earthquake. Journal of Transport Geography 2000;8:53–65.
[36] IMO. Guidelines for formal safety assessment (FSA)—for use in the IMO rule-making process. In: Organization IM, editor, 2002.
[37] Kontovas CA, Psaraftis HN. Formal safety assessment: a critical review. Marine Technology 2009;46(1):45–59.
[38] Oehmen J, et al. System-oriented supply chain risk management. Production planning and control 2009;20(4):343–61.
[39] IEA. Natural gas market review—optimizing investments and ensuring security in a high-priced environment, 2008.
[40] ECN. Long term gas supply in an enlarged Europe. In: Van Oostvoom F, editor. Energy Research Centre of the Netherlands; 2003.
[41] IEA. Natural gas review 2007. In: Hulst NV, editor. International Energy Agency; 2007.
[42] GIIGNL. The LNG industry in 2007. 2009 cited.
[43] IEA. World Energy Outlook, 2008.
[44] IEA. Natural gas information 2007. In: Reece M, editor. International Energy Agency; 2007.
[45] Vanem E, et al. Analyzing the risk of LNG carrier operations. Reliability Engineering & System Safety 2008;93:1328–44.
[46] IMO. SAFEDOR—design, operation and regulation for safety. 2009 cited. Available from 〈www.safedor.org〉.
[47] Melchers RE. On the ALARP approach to risk management. Reliability Engineering & System Safety 2001;71:201–8.
[48] Allen L, Boudoukh J, Saunders A. Understanding market, credit and operational risk—the value at risk approach. Malden: Blackwell Publishing; 2004.
[49] Haksöz Ç, Kadam A. Supply portfolio risk. Journal of Operational Risk 2009.
[50] Kleijnen JPC. Supply chain simulation tools and techniques: a survey. International Journal of Simulation & Process Modelling 2005;1(1/2):82–9.
[51] Kleijnen JPC, Smits MT. Performance metrics in supply chain management. The Journal of the Operational Research Society 2003;54(5):507–14.
[52] Trbojevic VM, Carr BJ. Risk based methodology for safety improvemt in ports. Journal of Hazardous Materials 2000;71:467–80.
[53] Hollnagel E. Barriers and accident prevention. Ashgate Publishing Limited; 2004.
[54] Mishan EJ, Quah E. Cost–benefit analysis. 5th ed.. Oxon: Routledge; 2007.
[55] Saleh JH, Marais K. Reliability: how much is it worth? Beyond its estibation or prediction, the (net) present value of reliability Reliability Engineering & System Safety 2006;91:665–73.
[56] DNV. Nakilat is an integral part of the LNG Supply chain. 2008 [cited 2010 2409]. Available from 〈http://eng.dnv.pl/industry/maritime/publicationsand downloads/publications/dnvtankerupdate/2008/no12008/Nakilatisaninte gralpartoftheLNGsupplychain.asp〉.
[57] Øien K. A framework for the establishment of organizational risk indicators. Reliability Engineering & System Safety 2001;74:147–67.