Research Article

Safety or Efficiency? An ECSO Framework of Traffic Organization Optimization for LNG Carriers Entering and Leaving Port

Fan Zhang ¹, Hang Yu ², Haoran Li ^{2,3}, Liqun Peng ² and Tuqiang Zhou ²

¹Beijing GOTECH ITS Technology Co., Ltd., Beijing, China

²School of Transportation and Logistics, East China Jiaotong University, Nanchang, China

³Intelligent Transport Research Center, Wuhan University of Technology, Wuhan, China

Correspondence should be addressed to Tuqiang Zhou; zhoutuqiang@126.com

Received 3 July 2021; Accepted 13 September 2021; Published 15 October 2021

Academic Editor: Bekir Sahin

Copyright © 2021 Fan Zhang et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Liquefied Natural Gas (LNG) is a clean, efficient, and economic energy, which is mainly transported by LNG carriers in the marine industry. Massive storage of LNG has led to public concern about the possible hazards of LNG carriers for people and facilities. This paper aims to determine the appropriate level of a safety zone and to develop an optimized traffic organization scheme. An innovative ECSO framework is proposed to deal with these two tasks. The results of the comparative analysis show that the influence degree of the optimized scheme is 21%, which is distinctly lower than the previous scheme (33%). To some extent, the proposed framework can provide meaningful enlightenments for stakeholders to improve port service level and ensure the safe operation of LNG carriers.

1. Introduction

Liquefied Natural Gas (LNG) mainly consists of methane, which is clean, efficient, and economic energy. As one of the greenest energies in the world, it can help protect the environment and reduce pollution. In recent years, the development of the LNG industry has already directly stimulated the development of related industries, such as shipping, shipbuilding, metallurgy, chemical industry, machinery and electronics, finance, insurance, and city gas, which will create significant economic and social benefits. However, the specific property of LNG can result in terrible accidents; unexpected events related to LNG release may lead to several potential threats such as asphyxiation, cryogenic burns, structural damage, rapid phase transitions (RPT), and even fires and explosions when the leaked gas contacts the ignition source [1, 2]. In case of ignition, there are four potential risk scenarios, namely, vapor cloud flash fire, poor fire, jet fire, and vapor cloud explosion [3, 4], which will bring catastrophic consequences.

The safety issue regarding LNG carriers has attracted great attention in the marine industry [5]. One of the typical

scenarios is LNG carriers entering and leaving port. Failure of any procedure during the process may expose the personnel, facilities, and environment to hazards [6]. Therefore, to ensure the operation environment, an appropriate level of safety zone needs to be determined, and traffic restriction is necessary. Accordingly, the service efficiency of the port decreases and the cost increases. Then, the most important question remains: how to balance the safety and efficiency during the process of LNG carriers entering and leaving port? Under the above background, the aims of this paper are twofold. The first objective is to determine an appropriate level of a safety zone in which the potential hazards involving LNG carriers entering and leaving port are required to be minimized. The second objective is then to develop an optimized traffic organization scheme, which can effectively reduce the influence of LNG carriers entering and leaving the port on the premise of safety.

2. Literature Review

2.1. Safety Zone. Due to the specific hazard of LNG, the consequence will be catastrophic when an emergency

happens involving LNG carriers. A safety zone is in place to prevent a natural gas release from igniting and leading to a serious incident.

The US Federal Regulation 33CFR165 sets the safety zone as navigable waters within a 1000-yard radius of LNG tankers, and all persons and vessels in the safety zone should comply with the instructions of the Captain of the Port representative or the designated on-scene patrol personnel.

Sandia National Laboratories defines for the US Department of Energy three Hazard Zones (also called, "Zones of Concern") surrounding LNG carriers. The largest zone is 2.2 miles/3,500 meters around the vessel, indicating that LNG ports must be located at least that distance from civilians.

The International Organization for Standardization (ISO) published the first standard related to the marine industry in 2010, which specified the requirements for ships, terminals, and port service providers to ensure the safe transit of an LNG carrier through the port area together with the safe and efficient transfer of its cargo [7]. Later, ISO/TS 18683 [1] recommends establishing a safety zone within which the access of all nonessential personnel is stringently restricted. However, it is only for LNG bunkering, and the ISO standards are limited to the provision of general information and do not offer quantified guidance.

Sniegocki [8] mentioned that Moving Safety Zone (MSZ) around a passing gas carrier is common practice. The MSZ of a gas carrier must be determined depending on the distance needed by the LNG carrier to stop safely. Vessels following the gas carrier astern should also keep clear for a similar distance allowing the gas carrier to reduce speed and maneuver without problems.

Tuttüren [9] from Det Norske Veritas (DNV) defined two types of safety zone: the safety zone required on the waterside is referred to as the Ignition Exclusion Zone (IEZ); and onshore safety zone is used for land clearance and requirements applicable to onshore side, determined by Quantitative Risk Analysis (QRA).

The Society of International Gas Tanker and Terminal Operators (SIGTTO) is one of the leading organizations that work out recommendations for the construction of new LNG terminals and areas, which has developed several global standards for LNG transport [10].

2.2. Port Traffic Organization and Optimal Operation. Due to the complexity and randomness of the port operation system, various factors have an impact on port traffic efficiency, such as arriving time of ships, unload time of ships, and weather conditions [11, 12].

Sun et al. [10] introduced a general simulation platform, named MicroPort, which aimed to provide an integrated and flexible modeling system for evaluating the operational capability and efficiency of different designs of seaport container terminals. Lin et al. [14] developed a mathematical model to minimize the weight of the ship's waiting time for the channel and applied the Genetic Algorithm (GA) to solve the model.

As for the efficiency improvement of port operation, Clausen and Kaffka [15] applied simulation to develop priority rules for handlings in inland port container terminals to optimize the operations in an overall system with all its stochastic influence and interactions. Zhang et al. [16] used the simulated annealing and multiple population GA to improve the efficiency of vessel transportation scheduling. Wang et al. [17] built a simulation model of the ships' navigation operation system to figure out how to improve the waterway through the capacity of coastal ports and how much each influencing factor can improve the capacity quantitatively.

Current research involving the traffic organization of LNG carriers is few. Regarding the influence of LNG carriers on other ships of the port, the majority of the analysis is from a qualitative perspective or considering the consequence caused by LNG physicochemical property [18, 19]. From an overall review for present LNG carriers' entering and leaving port traffic organization research, three key procedures can be summarized: (1) Traffic restriction is needed during the in-and-out port. Traffic restriction is to control the ship traffic of port area using Vessel Traffic Service (VTS) system, Closed-Circuit Television (CCTV) system of LNG port, Very High Frequency (VHF) communication, and so on. For that small traffic or complicated area, closure of navigation should be conducted. (2) When the LNG carrier is berthing or departing, enough tugboats should be offered. The type and power of tugboats are determined by different LNG carrier types. (3) During the LNG carrier's loading and unloading operation, the guard and emergency strategy should be considered. For instance, a guardship and anti-towing vessel should be prepared.

2.3. Navigation Risk of LNG Carriers. To some degree, risk can be regarded as the probability of a certain hazardous event multiplied by the consequence of the event [20, 21]. According to historic data [22, 23], most LNG carrier accidents occurred when they were under navigation and handling operations at the port.

Nwaoha et al. [24] developed a framework by incorporating risk matrix and fuzzy evidential reasoning (FER) method to investigate hazards associated with LNG carrier operations. Elsayed et al. [25] introduced the fuzzy Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) method into risk management of LNG carriers. Li and Tang [26] proposed a structural risk analysis model based on Bayesian belief network (BBN) to assess the risk of hull girder collapse of a membrane LNG carrier after grounding. Animah and Shafiee [27] reviewed and categorized 47 published journal articles about the problems associated with risk analysis of LNG facilities, the LNG carriers, and LNG fueled ships sector with 21 studies receiving the most attention in the LNG sector.

The main safety concern of LNG carriers is a possible leakage of large amounts of LNG or its vapor. Parihar et al. [28] developed a methodology for assessing the consequences of LNG release at deep-water port facilities. The consequences model determines the accidental release

scenario, the spill area, the resulting thermal hazard, and, in the case that LNG does not ignite immediately, the dispersion area until the lower flammability level is reached. Zhou et al. [20] proposed a novel FTA model for the analysis of the LNG carrier spill accidents; the quantitative evaluation is carried out by combining Cognitive Reliability and Error Analysis Method (CREAM) and Monte Carlo Simulation (MCS). Park et al. [2] examined the LNG leakage dispersion characteristics calculating the safety zone in a ship-to-ship LNG bunkering process.

2.4. Summary

- (1) A safety zone is in place to prevent a natural gas release from igniting and leading to a serious incident. The determination of the safety zone should consider both general regulations and the local navigation environment. Different countries, agencies, and ports have various standards, which means a lack of consistency.
- (2) Currently, effective theoretical research regarding traffic organization of LNG carriers are quite a few, and most of them focus on specific countermeasures for in-and-out port, safe operation allocation, emergency, and so on. Meanwhile, several port administrations adopt very simple ways for traffic restriction; that is, in case of an accident, closure of navigation is strictly executed. Obviously, this kind of extensive management is not applicable in the future when the traffic of LNG carriers increases.
- (3) Previous studies on the safety of LNG carriers were mostly based on consequence simulation. More importantly, the risk analysis is static and does not consider the influence of safety countermeasures on traffic organization.

3. Research Framework

The purpose of this study is to improve the traffic organization efficiency for LNG carriers entering and leaving ports on the premise of safety. To achieve this purpose, an ECSO framework is established, as shown in Figure 1.

The ECSO framework consists of four main parts, which derives from the initial letters of Environment analysis, Current navigation situation and Current scheme for in-and-out port, Safety zone determination, and Optimization scheme for traffic organization. The details are described as follows:

- (i) Environment analysis: environment analysis consists of the natural environment and port area profile. The former is a process for identifying all the natural elements that can affect the performance of the organization and evaluating the level of threat or opportunity they present. The latter includes waterway and anchorage of the port area.
- (ii) Current navigation situation: current navigation situation covers two major factors, namely, in-and-out port influence and ship traffic flow statistics.

Current scheme for in-and-out port: current scheme for in-and-out port refers to the present scheme for LNG carriers entering and leaving port, and the main contents include in-and-out port route, in-and-out port scheduling schemes, and in port berthing and out port unberthing.

- (iii) Safety zone determination: safety zone is part of the first layer of defense. The safe distances or exclusion zones are based on LNG vapor dispersion data and thermal radiation contours and other considerations as specified in local regulations, environment, and so on. Once the safety zone has been determined, further optimization traffic organization can be realized [29].
- (iv) Optimization scheme for traffic organization: optimization scheme for traffic organization includes in-and-out port organization, followed by a comparative analysis and safety precautions.

4. Case Study

A case study is used to demonstrate the effectiveness of the proposed ECSO framework. The Dagukou Port area in Tianjin Port has one of the largest specialized LNG export facilities in China and is located on Binhai New District, on the west of Bohai Bay. The LNG project has two appropriated berths ($266,000 \text{ m}^3$) for LNG carrier dock operation, one of them set as Floating Storage Regasification Unit (FSRU) recently. The designed traffic volume is 2,200,000 ton per year soon. Geographical location is shown in Figure 2.

Currently, the traffic restriction for LNG carrier entering and leaving the Dagusha Channel is 4-hour entering and 2-hour leaving restriction. Although this pattern can guaranty safety, the channel transit capacity is influenced.

The designed ship tonnages are from $10,000 \text{ m}^3$ to $266,000 \text{ m}^3$; designed FSRU ship tonnages are from $84,300 \text{ m}^3$ to $266,000 \text{ m}^3$. Details are shown in Table 1.

4.1. Environment Analysis

4.1.1. Natural Environment. (1) *Meteorology.* Due to the climate change in the last decade, measured values of Tianjin Tanggu Ocean Station from 2005 to 2010 are used for statistics analysis.

- (1) Temperature: Annual average value 13.1°C ; annual average maximum value 16.4°C ; annual average minimum value 10.9°C ; extreme maximum value 40.9°C ; extreme minimum value -13.5°C (note: minimum temperature -18.3°C on January 17th, 1953).
- (2) Precipitation: Annual average value 363.7 mm; annual average maximum value 491.1 mm; annual average minimum value 196.6 mm; maximum value in one day 157.2 mm (note: maximum precipitation 157.2 mm on July 30th, 1975).

FIGURE 1: ECSO framework.

Precipitation intensity $\geq$ light rain, 65.2 precipitation days per year; precipitation intensity $\geq$ moderate rain, 9.7 precipitation days per year; precipitation intensity $\geq$ heavy rain, 3.7 precipitation days per year; precipitation intensity $\geq$ intense rain, 1.0 precipitation days per year.

The precipitation of the port area has very distinct seasonal variations. Rainfall concentrates on July and August, which accounts for 58% of total precipitation per year. On the contrary, it seldom rains from December to next March, which only has a 3% proportion.

- (3) **Wind:** Wind is an unstable element in meteorology. To better reflect the wind situation in Tianjin Port, wind speed and wind direction were recorded 24 times per day from 2001 to 2010. It indicated that the direction of the prevailing wind is S, and the direction of the second prevailing wind is E. The frequencies are 9.89% and 9.21%, respectively. The

direction of the strong wind is E, and the direction of the second strong wind is ENE. The detailed wind rose diagram is shown in Figure 3.

- (4) **Thunderstorm:** Annual average thunderstorm is 14.6 days, and the thunderstorm often occurred in June and July.
- (5) **Fog:** annual average heavy fog day (visibility < 1 km) is 16.6 days, and the heavy fog often occurred in Autumn and Winter.
- (6) **Relative humidity:** average relative humidity 65%; maximum relative humidity 100%; minimum relative humidity 3%.

(2) *Hydrology.*

- (1) **Tide:** Annual maximum value 5.81 m (September 1st, 1992); annual maximum value -1.08 m (December 18th, 1957); annual average high value 3.74 m; annual average low value 1.34 m; annual average sea level 2.56 m; annual maximum tidal range 4.37 m

FIGURE 2: Overview of geographical location.

(October 1980); annual average tidal range 2.40 m; design high water level 4.30 m; design low water level 0.50 m; extreme high water level 5.88 m; and extreme low water level -1.29 m.

- (2) Wave: Direction of the prevailing wave is ENE and E. The frequencies are 9.68% and 9.53%, respectively. The direction of the strong wave is ENE. The detailed wave rose diagram is shown in Figure 4.
- (3) Sea current: Rising tide flow W-NW; falling tide flow $E \sim SE$; average flow velocity of tidal segment < 0.3 m/s.

(3) *Geological Landform.*

- (1) Sediment sources: on both sides of the shallow
- (2) Sand content: the sand content changes with the weather and seasons
- (3) Sediment grain size: median value 0.003–0.019 mm; average median value 0.0098 mm; sand 9.2%, silt 52.3%, clay 38.5%

4.1.2. Port Area Profile. (1) *Waterway.* As shown in Figure 1, the channel for LNG carriers, namely, the Dagusha Channel, is located between the Nanjing Port area and the Dagukou Port area in Tianjin Port. The waterway is designed as 32 km length, 275 m bottom width, -14.5 m bottom elevation, and side slope grade 1 : 5. The water can satisfy 100,000-ton ship for the in-and-out port.

(2) *Anchorage.* LNG emergency anchorage is a trapezoidal water area, located at the east of 100,000-ton ship level anchorage. The square is about 2.7 km^2 and 2230 m from Tianjin Port's main channel.

4.2. Current Navigation Situation and Current Scheme for In-and-Out Port

4.2.1. Current Navigation Situation. (1) In-and-Out Port Influence.

- (1) Due to the hazard of LNG, traffic restriction is conducted during LNG carriers entering and leaving port, and any ship is prohibited to enter MSZ. Normal navigation is severely influenced.
- (2) The fishing-boat waterway is located 100 m north of the project, and communication is difficult. Meanwhile, several sand and gravel carriers will exist near the Dagusha Channel. During FSRU berthing operation, safety precautions should be taken to prevent ships from passing through.

4.2.2. Current Scheme for In-and-Out Port. (1) *In-and-Out Port Route.* The route for LNG carriers entering port starts at Laotieshan Waterway, and a 35° veer is needed, as shown in Figure 5. The in-and-out route is about 11 nmiles, which allow LNG carrier having enough time for course adjustment.

(2) *In-and-Out Port Scheduling Schemes.* Currently, the LNG carrier enters and leaves the port at 0800; traffic restrictions are 4 hours and 2 hours, respectively. Before the waterway inflection point, the navigational speed of an LNG carrier is not allowed to surpass 10 kN.

(3) *In Port Berthing.*

- (1) Berth method: Turn around and berth on left side.
- (2) Waterway navigation: From emergency anchorage to main channel, speed at 8–11 kN. Speed at 8–9 kN in Dagusha Channel. Pass through bulwark at 7 kN. When approaching 237# buoy, speed at 4 kN. When ship stem enters circumferential boundary, speed at 2.5–3.
- (3) Tugboat allocation and manipulation.

When an LNG carrier of $80,000 \text{ m}^3$ and above is berthing, 3–5 tugboats can assist.

(4) *Out Port Unberthing.*

(1) *Manipulation*

When the LNG carrier arrives at the forefront, the tugboat stem should increase the drag force. After speeding at 4 kN, remove other tugboats. When passing through bulwark, speed at 8–9 kN and leave the port.

(2) *Tugboat allocation.*

Before the LNG carrier unmoors, 5 tugboats should be prepared at the appropriate position of the ship's starboard.

(3) *Emergency unberthing.*

When LNG carrier is unberthing, weather forecast should be paid enough attention. Especially for the typhoon, wind level and wind direction can be constantly watched out for. If vessel age is larger than 10 years, the speed should smaller than 8 kN.

4.3. Safety Zone Determination. After a comprehensive literature review and wide range investigation survey in China, the safety zone has been determined (the details are shown in

TABLE 1: Designed representative LNG carrier type.

	Ship tonnage (m ³)	Length overall (m)	Breath molded (m)	Depth molded (m)	Load draught (m)
LNG carrier	10,000	137.1	19.8	11.5	5.8
	30,000	175	28.1	18.5	7.5
	84,300–140,000	281	42.00	27.50	11.70
	140,000–155,000	298	48.00	27.50	12.30
	217,000	315	50.00	27.00	12.30
	266,000	345	53.80	27.00	12.20

FIGURE 3: Wind rose diagram of Tianjin Port (2001–2010).

Table 2) it is worth mentioning that the local environment and current port situation are taken into consideration during the process of safety zone determination.

4.4. Optimization Scheme for Traffic Organization

4.4.1. In Port Scheme. The imports LNG to Tianjin port are mainly from Austrian, Qatar, Yemen, and the US. LNG carriers enter Bohai Bay through Laotieshan Waterway, and when approaching the Dagusha channel, they slow down and wait for the pilot officer onboard.

According to berthing operation time analysis, the AC section is 11.3 nmiles; then, it will take 1.1 hours for the general ship to pass through with 10 kN. Therefore, LNG carrier is recommended to keep at least a 1-hour time interval with ahead ship (as shown in Figure 6).

Based on the above description, the voyages from LNG dock to 1 dock basin and from 1 dock basin to E point are 4.5 nmiles and 2.6 nmiles, respectively. Investigation survey indicated that the general ship will take 0.3–0.5 h to cast loose and remove the tugboat. The time schedule is shown in Table 3.

According to Table 3, it will take only 1 h for the ship at west 1 dock basin to arrive LNG dock front area. As for the

east side, 2.5 h traffic restriction is recommended. The above schedule can be further optimized based on the real situation of the port.

4.4.2. Out Port Scheme. The maritime administrative authority will release a navigation warning 12 hours in advance. Before LNG carrier is unberthing, AIS, VTS, and VHF are used to make sure there is no in port ships. It takes 1.9–2.0 h for an LNG carrier's out port. Therefore, a 2 h traffic restriction is recommended, as shown in Figure 7.

LNG carriers leaving has a relatively smaller influence on the same direction ship. An MSZ is set (stem 1 nmile, stern 0.5 nmile), and a guard for navigation is conducted.

4.4.3. Comparative Analysis. Currently, no night navigation is allowed in the Dagukou Port area. According to the survey data, there are about 90 ships per day in port area. The comparison is conducted, as shown in Table 4.

It is obvious that the optimized scheme will distinctly improve the navigation efficiency of the Dagusha Channel.

4.4.4. Safety Precautions. As the traffic organization scheme has been changed, safety precautions should be strengthened as follows:

- (1) The port operators should provide dynamic information of LNG carriers for marine admirations and pilot department.
- (2) When the LNG carrier is entering or leaving port, a coastal patrol vessel and two snag boats are needed to provide.
- (3) Emergency response plan should be renewed according to the optimized scheme, together with emergency resources in port and port environment.
- (4) When the LNG carrier enters the Dagusha Channel, MSZ should be set as shown in Figure 8.

5. Discussions

The paper proposes an innovative ESCO framework to improve the traffic organization efficiency for LNG carriers entering and leaving port on the premise of safety. The four elements, namely, environment analysis, current navigation situation and current scheme for in-and-out port, safety zone determination, optimization scheme for traffic

FIGURE 4: Wave rose diagram of Tianjin Port.

FIGURE 5: In-and-out port route (Laotieshan-Dagusha).

organization, are described, followed by a case study of Dagukou Port area in Tianjin Port. The result of the comparative analysis shows that the optimized scheme will distinctly improve navigation efficiency of the Dagusha Channel.

The determination of safety zone covers many aspects of the environment analysis, local regulations, and a wide range of investigation survey [30]. After the key safety element has been assured, an optimized scheme for traffic organization of LNG carriers and other ships is given. The result of the

comparative analysis shows that the influence degree of the optimized scheme is 21%, which is distinctly lower than the previous scheme (33%). Finally, safety precautions are renewed, with the coordination of a new optimization scheme.

The proposed ESCO framework is an initial trial to relieve contradiction between safety and efficiency during the process of LNG carriers entering and leaving port. Quantitative analysis, especially for comparative analysis is not considered. More detailed information regarding the

TABLE 2: Safety zone determination.

No.	Port or standard		MSZ		Note
			Bow (nm)	Stern (nm)	
1	Domestic port	Dalian Port	1	1	500
2		Meizhou Bay	1.5	0.5	750
3		Yangshan Port	6-time SL	6-time SL	4-time SL
4		Guangzhou Port	4-time SL	2-time SL	—
5		Zhoushan Port	1	1	500
6		Rudong Port	1	1	1000
7		Shenzhen Bay	0.8	0.8	1500
8	Foreign port	Naragansett Bay	2	1	914.4
9		Chesapeake Bay	0.25	0.25	457.2
10		SAN Juan Port	0.5	0.5	926
11		Savannah River	2	2	3704
12		Phillips	2	2	3704
13		Boston Port	2	1	457.2
14		San Pedro Bay	0.49	0.25	457.2
15		Cameron Island	2	1	-
16		Savannah	0.03	0.03	55.6
17		Massachusetts	0.27	0.27	500
18		Montoir Port	2	2	Not allowed
19		Snohvit	1.5	1.5	2778
20	Tianjin administrative provision	1	0.5	150	
21	China administrative provision	8-time SL	3-time SL	1-time SL	
22	SIGTTO	1.5	0.5	—	
23	Transport Canada	1	1	250	
24	This project	1	0.5	—	One-way

FIGURE 6: In port scheme for traffic organization.

TABLE 3: Time schedule for the general ship.

Unberthing period	Cast loose and remove tugboat	Acceleration	From 1 dock basin to LNG dock front area
Time	0.3~0.5 h	0.25~0.3 h	0.45 h
Total time		1.0 h~1.25 h

FIGURE 7: Out port scheme for traffic organization.

TABLE 4: Comparative analysis.

	Daily traffic flow in port area (ships)	Daily traffic flow with LNG carriers entering or leaving port (ships)	Reduced ships	Influence degree (%)
Previous scheme	90	60	30	33
Optimized scheme	90	71	19	21

FIGURE 8: MSZ of LNG carrier.

investigation survey should be strengthened. Furthermore, simulation is needed during the process of safety zone determination. Despite these limitations, the framework can provide some enlightenments for stakeholders to improve port service level and ensure the safe operation of LNG carriers [31–33].

Data Availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research was supported by National Key R&D Program of China (Grant No. 2020YFE0201200), Public Open Project of National Technical Committee of Automotive Standardization (Grant no. bz202002), and Science and Technology Research Project of Education Department of Jiangxi Province (Grant no. GJJ200670).

References

- [1] International Organization for Standardization, *Guidelines for Systems and Installations for Supply of LNG as Fuel to Ships*, International Organization for Standardization, Geneva, Switzerland, 2015.
- [2] S. Park, B. Jeong, J. Y. Yoon, and J. K. Paik, "A study on factors affecting the safety zone in ship-to-ship LNG bunkering," *Ships and Offshore Structures*, vol. 13, no. 1, pp. 1–10, 2018.
- [3] O. N. Aneziris, I. A. Papazoglou, M. Konstantinidou, and Z. Nivolianitou, "Integrated risk assessment for LNG terminals," *Journal of Loss Prevention in the Process Industries*, vol. 28, pp. 23–35, 2014.
- [4] O. Aneziris, I. Koromila, and Z. Nivolianitou, "A systematic literature review on LNG safety at ports," *Safety Science*, vol. 124, Article ID 104595, 2020.
- [5] R. Bubbico and E. Salzano, "Acoustic analysis of blast waves produced by rapid phase transition of LNG released on water," *Safety Science*, vol. 47, no. 4, pp. 515–521, 2009.
- [6] E. Vanem, P. Antão, I. Østvik, and F. D. C. de Comas, "Analysing the risk of LNG carrier operations," *Reliability Engineering & System Safety*, vol. 93, no. 9, pp. 1328–1344, 2008.

- [7] International Organization for Standardization, *Petroleum and Natural Gas Industries—Installation and Equipment for Liquefied Natural Gas—Ship-To Shore Interface and Port Operations*, International Organization for Standardization, Geneva, Switzerland, 2010.
- [8] H. Sniegocki, “The requirements for safe traffic and manoeuvring in approaches to the port of Swinoujscie and the outer port of Swinoujscie with particular emphasis on LNG vessels,” *Journal of KONES Powertrain and Transport*, vol. 20, no. 4, pp. 419–423, 2013.
- [9] J. P. Tutturén, “FSRU-Critical link in Global LNG Supply chain,” in *Proceedings of the Society of International Gas Tanker and Terminal Operators Panel Meeting*, Houston, Texas, October 2017.
- [10] M. Perkovic, L. Gucma, M. Przywarty, M. Gucma, S. Petelin, and P. Vidmar, “Nautical risk assessment for LNG operations at the port of koper,” *Strojnikovski vestnik—Journal of Mechanical Engineering*, vol. 58, no. 10, pp. 607–613, 2012.
- [11] B. Wu, X. Yan, and C. G. Soares, “An evidential reasoning-based CREAM to human reliability analysis in Maritime accident process,” *Risk Analysis*, vol. 37, no. 10, pp. 1936–1957, 2016.
- [12] Y. He, C. Sun, H. Huang et al., “Safety of micro-mobility: riders’ psychological factors and risky behaviors of cargo TTWs in China,” *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 80, pp. 189–202, 2021.
- [13] Z. Sun, L. H. Lee, E. P. Chew, and K. C. Tan, “MicroPort: a general simulation platform for seaport container terminals,” *Advanced Engineering Informatics*, vol. 26, no. 1, pp. 80–89, 2012.
- [14] J. Lin, X. Zhang, and Y. Yin, “Optimization of ship scheduling based on one-way waterway,” in *Proceedings of the 14th International Conference on Algorithms and Architectures for Parallel Processing (ICA3PP)*, pp. 479–486, Dalian, China, August 2014.
- [15] U. Clausen and J. Kaffka, “Development of priority rules for handlings in Inland port container terminals with simulation,” *Journal of Simulation*, vol. 10, no. 2, pp. 95–102, 2016.
- [16] X. Zhang, J. Lin, and Z. Guo, “Vessel transportation scheduling optimization based on channel-berth coordination,” *Ocean Engineering*, vol. 112, pp. 145–152, 2016.
- [17] W. Wang, Y. Peng, Q. Tian, and X. Song, “Key influencing factors on improving the waterway through capacity of coastal ports,” *Ocean Engineering*, vol. 137, pp. 382–393, 2017.
- [18] M. Zhang, D. Zhang, F. Goerlandt, X. Yan, and P. Kujala, “Use of HFACS and fault tree model for collision risk factors analysis of icebreaker assistance in ice-covered waters,” *Safety Science*, vol. 111, pp. 128–143, 2019.
- [19] M. Zhang, F. Conti, H. Le Sourné et al., “A method for the direct assessment of ship collision damage and flooding risk in real conditions,” *Ocean Engineering*, vol. 237, Article ID 109605, 2021a.
- [20] T. Zhou, C. Wu, J. Zhang, and D. Zhang, “Incorporating CREAM and MCS into fault tree analysis of LNG carrier spill accidents,” *Safety Science*, vol. 96, pp. 183–191, 2017.
- [21] E. Akyuz, “A marine accident analysing model to evaluate potential operational causes in cargo ships,” *Safety Science*, vol. 92, pp. 17–25, 2017.
- [22] L. H. Anay, “A review of large-scale LNG spills: experiments and modeling,” *Journal of Hazardous Materials*, vol. 132, pp. 119–140, 2006.
- [23] T. Elsayed, H. Lehetá, and K. Marghany, “Multi-attribute risk assessment of LNG carriers during loading/offloading at terminals,” *Ships and Offshore Structures*, vol. 4, no. 2, pp. 127–131, 2009.
- [24] T. Nwaoha, Z. Yang, J. Wang, and S. Bonsall, “Adoption of new advanced computational techniques to hazards ranking in LNG carrier operations,” *Ocean Engineering*, vol. 72, pp. 31–44, 2013.
- [25] T. Elsayed, K. Marghany, and S. Abdulkader, “Risk assessment of liquefied natural gas carriers using fuzzy TOPSIS,” *Ocean Engineering*, vol. 9, pp. 355–364, 2014.
- [26] X. Li and W. Tang, “Structural risk analysis model of damaged membrane LNG carriers after grounding based on Bayesian belief networks,” *Ocean Engineering*, vol. 171, pp. 332–344, 2019.
- [27] I. Animah and M. Shafiee, “Application of risk analysis in the liquefied natural gas (LNG) sector: an overview,” *Journal of Loss Prevention in the Process Industries*, vol. 63, Article ID 103980, 2020.
- [28] A. Parihar, C. Vergara, and J. K. Clutter, “Methodology for consequence analysis of LNG releases at deepwater port facilities,” *Safety Science*, vol. 49, no. 5, pp. 686–694, 2011.
- [29] Y. He, S. Yang, C. Y. Chan, L. Chen, and C. Wu, “Visualization analysis of intelligent vehicles research field based on mapping knowledge domain,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 22, no. 9, pp. 5721–5736, 2021.
- [30] M. Zhang, J. Montewka, T. Manderbacka, P. Kujala, and S. Hirdaris, “A big data analytics method for the evaluation of ship-ship collision risk reflecting hydrometeorological conditions,” *Reliability Engineering & System Safety*, vol. 213, Article ID 107674, 2021b.
- [31] B. Jeong, B. S. Lee, P. Zhou, and S. M. Ha, “Evaluation of safety exclusion zone for LNG bunkering station on LNG-fuelled ships,” *Journal of Marine Engineering and Technology*, vol. 16, no. 3, pp. 121–144, 2017.
- [32] United States Department of Energy, *Liquefied Natural Gas Safety Research. LNG Safety Research Report to Congress*, https://www.energy.gov/sites/prod/files/2013/03/f0/doi_lng_safety_research_report_to_congre.pdf, United States Department of Energy, Washington DC, WA, USA, 2012, https://www.energy.gov/sites/prod/files/2013/03/f0/doi_lng_safety_research_report_to_congre.pdf.
- [33] T. Zhou, W. Wu, L. Peng et al., “Evaluation of urban bus reliability on variable time horizons using a hybrid deep learning method,” *Reliability Engineering & System Safety*, vol. 2021, no. 9, pp. 5721–5736, 2021.