Safe zone design in a truck-to-ship LNG bunkering

Sung-In Park[a,b] and Jeom Kee Paik[a,c,d*]

[a] Department of Naval Architecture and Ocean Engineering, Pusan National University, Busan, Republic of Korea

[b] Department of the System Safety Research, Energy Technology R&D Group, Korea Shipbuilding & Offshore Engineering Co., Ltd., Seoul, Republic of Korea

[c] The Korea Ship and Offshore Research Institute (Lloyd's Register Foundation Research Centre of Excellence), Pusan National University, Busan, Republic of Korea

[d] Department of Mechanical Engineering, University College London, London, United Kingdom

[*] Corresponding author. Tel.: +44 20 7679 3174. *Email address: j.paik@ucl.ac.uk* (J.K. Paik).

Abstract:

This paper is a sequel to the authors' article (Park et al., 2020) which addressed a hybrid method for the safe zone design of a floating LNG-fueled power plant against unwanted LNG or NG leakage during bunkering. The aim of this paper is to develop a design method for the safe zone layout of LNG-fueled ships during bunkering, where a hybrid method is suggested as a combination of two industry practice, deterministic and risk-based approaches. A limitation of the deterministic approach is pointed out and the solutions are suggested with its practical application method and an alternative solution, the hybrid method. The applicability of the proposed methods is demonstrated with an illustrative example design on the safe zone layout of a truck-to-ship bunkering. Insights and findings obtained from the study are documented and the benefits of using the hybrid method are presented by comparing with the deterministic method.

Keywords: LNG, bunkering, safety zone, security zone, risk assessment, gas dispersion analysis.

1. Introduction

To meet the requirements of the International Maritime Organization (IMO) regulations for green shipping (IMO, 2019), alternative fuels such as natural gas (NG), hydrogen gas, ammonia, bio fuel, etc. are considered for ship propulsion as a traditional fuel oil is hard to meet them. LNG (liquefied NG) is one of the most popular sources for that purpose, and more and more LNG fuel supplying is needed for an increasing number of LNG-fueled ships (Figure 1). Various techniques of LNG fuel supplying (bunkering) into ship exist and the International Standardization for Organization (ISO) defines three standard types of LNG bunkering as shore-to-ship, truck-to-ship and ship-to-ship (ISO, 2015). Figure 2 shows the schematic plot of the standard LNG transfer systems.

(a) (b)

Figure 1. Various LNG-fueled ships: (a) 114,000 DWT LNG fueled crude oil tanker (HSHI, 2017) and (b) 50,000 DWT LNG-fueled bulk carrier (HSHI, 2018)

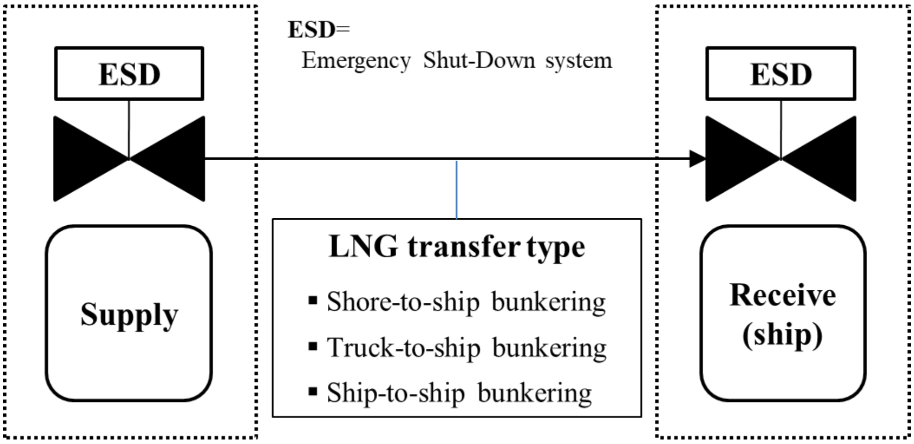


Figure 2. Standard types of LNG transfer into ships

Because risk always exists wherever hazards associated with unwanted release of LNG during bunkering, a set of measures should be prepared to secure the safety of working personnel, asset and surrounding environment. In regard to this, the International Maritime Organization (IMO) and members of the International Association of Classification Societies (IACS) introduce the necessity of a safe layout design in LNG bunkering through their guidelines on the design of LNG-fueled ships (ABS, 2019; DNV GL, 2015; IMO, 2015; LR, 2019). As a fundamental safety barrier in LNG bunkering, a safe zone should be established and this aims to provide the safety distance inside and outside the zone by limiting personnel access and working activities in the specific area. For the definition of this safe zone, the ISO (2015) suggests the concept of safety and security zones in LNG bunkering, as described in Table 1 and the Society for Gas as a Marine Fuel, SGMF (2018) suggests an extended concept, called the controlled zone, consisting of 5 detail zones including a hazardous zone as defined by the International Electro-technical Commission, IEC (2015), safety & security zones similar to the ISO concept, a marine (exclusion) zone and an external zone. Table 2 explains a detail description of the controlled zone and Figure 2 presents its schematic representation with focus on truck-to-ship bunkering.

Table 1. Definitions of safety and security zones in LNG bunkering.

Safety zone	area around the bunkering station where only dedicated and essential personnel and activities are allowed during bunkering
Security zone	area around the bunkering facility and ship where ship traffic and other activities are monitored (and controlled) to mitigate harmful effects

Table 2. Definition of the controlled zone in LNG bunkering.

Hazardous zone	The hazardous zone is a three-dimensional space in which a combustible or explosive atmosphere can be expected to be present frequently enough to require special precautions for the control of potential ignition sources. Hazardous zones are always present but addressed via appropriate design techniques and safety practices.
Safety zone	The safety zone can be defined as the three-dimensional envelope of distances inside which the majority of leak events occur and where, in exceptional circumstances, there is a recognized potential for a leak of natural gas or LNG to harm life or damage equipment/infrastructure. The zone is temporary by nature, present only during bunkering. It may extend beyond the gas-fueled ship/LNG road tanker/bunker vessel, interconnecting pipework, and so on, and will be larger than the hazardous zone.
Monitoring & security area	The monitoring & security area is defined as the three-dimensional space inside which activities (including people and vehicle movements) need to be identified and monitored to ensure that they do not affect the safety of the bunkering operation by encroaching on the safety zone of the gas-fueled ship, quayside or LNG bunkering infrastructure. Its primary purpose is to prevent impacts from the actions of people not involved in the bunkering process.

Marine (exclusion) Zone	The purpose of the marine exclusion zone is to protect the bunkering vessel from other marine traffic, primarily by defining minimum distances and speeds for passing vessels. Definition of the marine exclusion zone is for each port to decide and implement in port rules, based on specific port and ship studies. All ships and bunker vessels must comply with these rules in the normal way.
External zone	In some jurisdictions – for example, much of Europe – an external zone is required. A port cannot influence how the general public behaves outside the port area so the risk level outside must be kept low. This zone is defined by the level of risk general members of the public can be exposed to, based on local regulatory requirements.

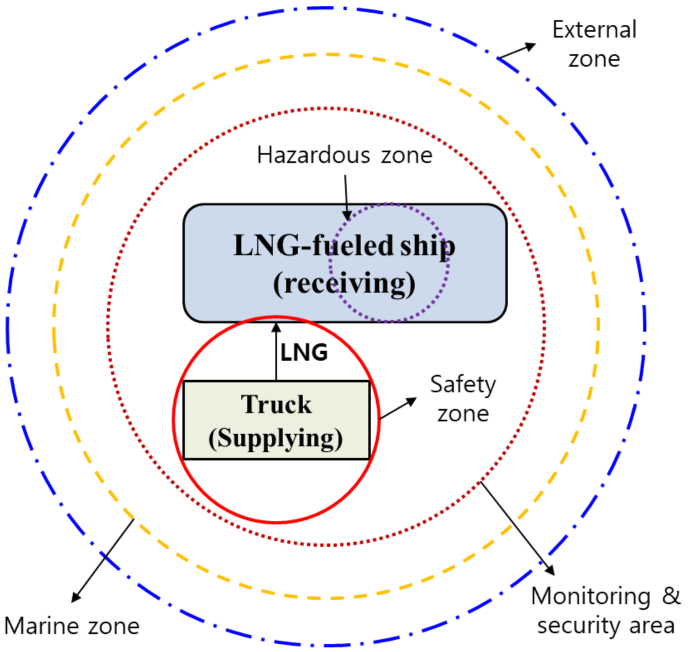


Figure 3. Schematic representation of the controlled zone in LNG bunkering

Currently, the ISO standards are available for the design of the safe zone in LNG bunkering (ISO, 2015), where two methods named as deterministic and risk-based approaches are introduced with their applicable bunkering conditions. The deterministic approach can be generally adopted in the normal situation but the risk-based approach is highly demanding to apply in bunkering operations with special issues (DNV GL, 2015; ISO, 2015). Both approaches have pros and cons for their applications. The deterministic approach provides a compact procedure but resulted safe zone layout may take a level of inaccuracy due to a deterministically defined LNG leakage scenario and coarse technique of LNG release simulation. In case of the risk-based approach, it can provide a high quality on resulted layout using the qualitative risk assessment (QRA) which has been delicately established in industries (CMPT, 1999; US NRC, 2016) but this methodology takes lots of cost and time and may not be appropriate in the practical engineering. Some limited researches exist on the safe zone layout in LNG bunkering but they are all related to the risk-based approach. Jeong et al. (2018) pointed out the absence of detail guideline for the design of the exclusion zone in LNG bunkering and suggested the integrated quantitative risk assessment method as a supplement to the risk-based approach. Park et al. (2018) presented the technique of computational fluid dynamics (CFD) simulation for the design of the safety zone in the risk-based approach. Park et al. (2019) pointed out a weakness point of the risk-based approach and proposed a hybrid type method as an alternative to the risk-based approach utilizing more simplified frequency and consequence analysis techniques. As a sequential work, the authors have conducted a study on the deterministic approach and the output is suggested in this paper. A weak point of the deterministic approach is verified and the way of improvement is suggested as the practical application of the deterministic approach. Further, a hybrid type method is developed as an alternative solution and its applicability is discussed. An illustrative example on the safe zone design of LNG bunkering between a tank-lorry and a LNG-fueled ship is shown to demonstrate the standard design of the safe zone using both of deterministic and hybrid approaches.

2. Industry Practices for the Safe Zone Design in LNG Bunkering

2.1 Deterministic approach

Figure 4 presents a general procedure for the deterministic approach to design the safe zone in LNG bunkering. When bunkering is planned with standard type operations (Figure 2) and only LNG is transferred from a supplying facility to a demanding ship, then the deterministic approach is utilized to design the safe zone layout.

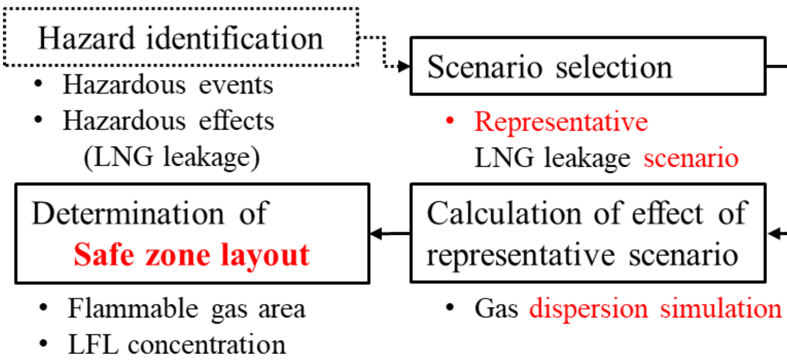


Figure 4. General procedure of the deterministic approach.

This method defines the safe zone as the area within the distance to the specific level of lower flammable limit (LFL) concentration as determined by a recognized and validated dispersion model for the maximum credible LNG release scenario as defined as part of a hazard identification (HAZID) study (DNV GL, 2015). In this method, the safe zone is considered as the area of possible flammable conditions such as fire and explosion and the personnel access and activities are closely controlled to prevent any ignition in the area. A specific case of unwanted LNG release is defined as the representative scenario and this is defined in consideration of characteristics in bunkering as below (DNV GL, 2015; ISO, 2015):

- transfer rates and inventory in the bunkering facilities;
- operational modes
- implemented safeguards
- distance to other facilities or operations
- location-specific and representative weather conditions

An example of the scenario selection may refer to the ISO guidance (ISO, 2015) and this relates to LNG release of trapped volume inside the LNG hose or piping between emergency shut-down (ESD) valves. The gas dispersion simulation is conducted for the selected scenario and the safe zone layout is designed with an effected area of the specific level of LFL concentration.

Someone may consider the deterministic approach as a short and straightforward method but its application in the practical engineering is not for clear. There is a challenging issue in this method in relation to define "representative scenario". As an example, when LNG is transferred via a hose or piping from a bunkering facility to a demand ship, it is unclear to define which size of the leak is made on the transfer line including, valve, flange and other instrument connections due to any damage on those systems. If a leak size or a representative leak scenario is simply selected as the whole line rupture, large, medium or small size leaks, dispersed gas boundaries and resulted safe zone layouts will vary considerably. Thereby, some justification should be provided on the selected scenario and then the comprehensive understanding can be made on the designed safe zone layout. Regarding to this issue, the authors have agonized a wise solution for the issue on the scenario selection and the latter of this paper will introduce a practical application of the deterministic approach and a newly developed hybrid method as an alternative solution of the deterministic approach.

2.2 Risk-based approach

Figure 5 presents a general procedure of the risk-based approach to design the safe zone in LNG bunkering. In case of bunkering with special issues such as simultaneous cargo operations, with passengers on-board or etc., the risk-based approach should be chosen using the QRA to demonstrate the effects of special conditions during bunkering (ISO, 2015).

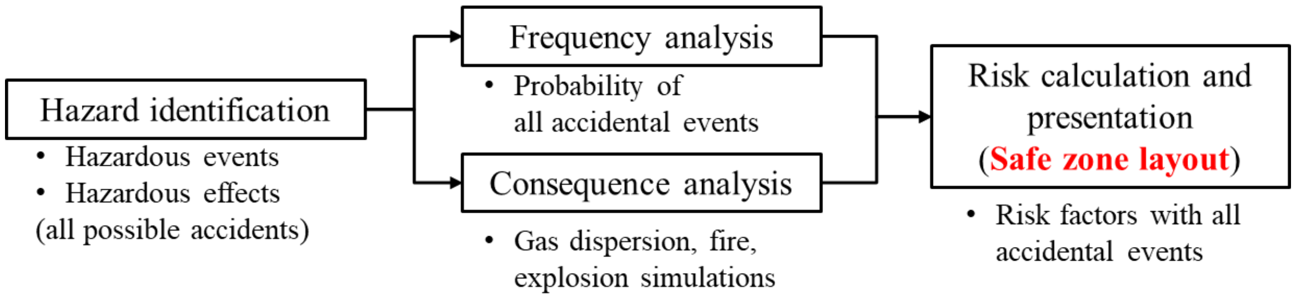


Figure 5. General procedure of the risk-based approach.

While the deterministic approach generally focuses on the accidental leakage from LNG transfer line and verifies the effect of combustible gas dispersion for the safe zone layout, the risk-based approach identifies a detail of hazardous situations coming from not only LNG transfer but other operations during bunkering. Hazardous situations may vary in association with the characteristics of supplying and demand facilities and frequency & consequence of all possible accidents are considered in this method. The risk level is estimated with probabilities and consequences of total accidental events and then the safe zone is designed considering the possible exposure of personnel to accidents and fatal conditions. Under the risk-based approach, the resulted safe zone has a high reliability but the only fault is that this requires extensive time and cost for design due to its complicated engineering. Sometimes, the safe zone needs to be defined as early as possible to identify a required area for the facility operation and the risk-based approach is not an effective solution for that situation. Regarding to this issue, Park et al. (2020) suggested the hybrid method as an alternative solution to the risk-based approach to arrange the safe zone of a floating LNG-fueled power plant in the early stage of the project development.

Meanwhile, the offshore industry has accumulated the statistics of historical process accidents relevant to leakage of piping, flange, valve and other process equipment (IOGP, 2010; SINTEF 2015; HSE, 2010 & 2019) and these are utilized as the input data for frequency analysis and leak scenario selection in the QRA. In case of the LNG industry, there is not enough data accumulated for that purpose and this may limit the application of the risk-based approach. Regarding to this issue, some researches have mentioned the necessity of systematically collected accidental data in the LNG industry and suggested to use the offshore data in application of the risk-based design on LNG systems (Davies & Fort, 2013; Park et al., 2020; Spouge, 2015). Detail methodologies and techniques used in the QRA and the risk-based approach can be achieved from the previous researches and literature (CMPT, 1999; DNV GL, 2015; ISO, 2015; Jeong et al., 2018; Paik, 2019; Park et al., 2018; Park et al., 2020; Vinnem, 2014).

3. Hybrid Approach as an Alternative to Deterministic Approach

The DNV GL (2015) established its design practice for the development of LNG bunkering facility and this introduces a hybrid approach as one of the design methodology for the safe zone layout along with deterministic and risk-based approaches. This concept intends to add some probabilistic factors on the deterministic approach to grant more reliability on its resulted safe zone layout. Inspired by this hybrid approach, the authors propose a new, hybrid type method as an alternative solution to the deterministic approach. This hybrid method is basically based on the deterministic approach and takes an advantage of the risk-based approach which considers the frequency or the probability of possible LNG leakage to define possible LNG leak scenarios. By adding a technical basis on the selected leak scenario, this hybrid method aims to derive a general agreement on resulted the safe zone layout comparing to the deterministic approach. Figure 6 shows a procedure of the hybrid approach which takes additional step into the procedure of the deterministic approach (Fig. 4).

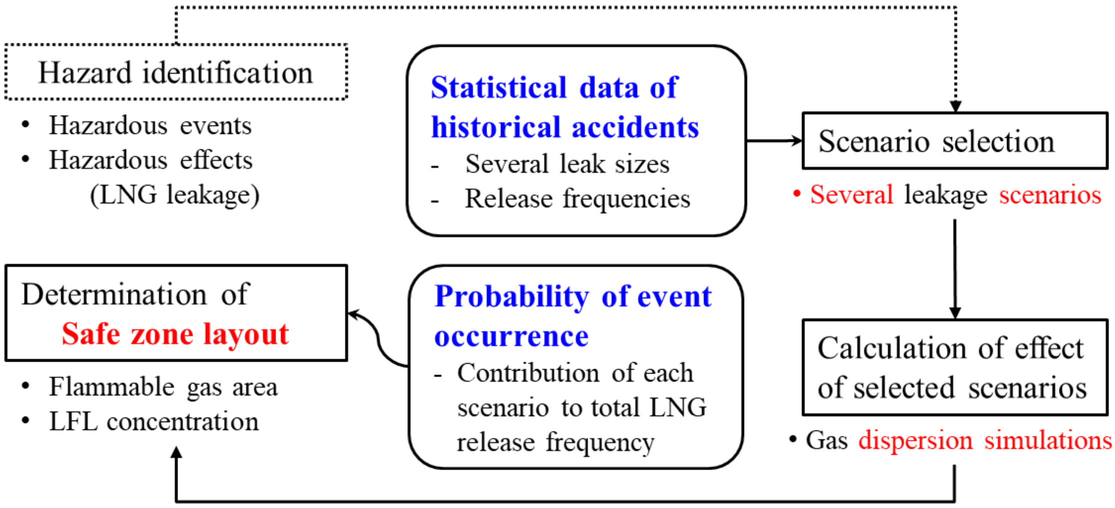


Figure 6. Procedure of the hybrid approach

As same as the deterministic approach, a credible LNG leakage is discussed at the HAZID session and this can be generally defined as a failure of the LNG transfer line connected between a bunkering facility and a demand ship. A different point is that in case of the deterministic approach, a single leak size is designated as the representative leak scenario on the basis of an engineering judgement but the hybrid approach tries to consider several possible leak sizes and credible scenarios in relation to the probability of their occurrence. Like as the deterministic approach, in the hybrid method, the safe zone indicates the area of possible flammable condition and frequency of LNG release is assumed as probability of flammable accident (flash fire) without consideration of ignition probability.

Below descriptions provide a detail procedure of the hybrid method:

(a) Based on a size (diameter) of LNG transfer lines, a set of leak hole sizes and their probability of leak occurrence (frequency) are defined using the statistics on the historical accidental data (variables A_n and B_n in Table 3). As mentioned in the previous chapter, there are many available statistical data of process accidents in the offshore industry and those provide possible leak sizes and their frequencies in association with diameter of a target piping system. As an example, for a diameter of 300 mm piping, five categories of leak sizes consisting of 1-3 mm (minor case), 3-10 mm (small case), 10-50 mm (medium case), 50-150 mm (large case) and over 150 mm (rupture case) can be considered with the International Association of Oil & Gas Producers, IOGP (2010) data in Table 4.

(b) Contribution of each leak frequency to the total probability of LNG release is calculated with Eq. (1) (variable C_n in Table 3). It should be noted that the example reference statistics (IGOP, 2010) assumes 5 leak size categories as minor leak, small leak, medium leak, large leak and rupture case and thereby the calculation of Equation (1) is repeated for five times following sub-variables from 1 (i=1) to 5 (n=5). This procedure may vary with the selected statistical data in application of the hybrid method.

(c) Defined leak sizes are considered as possible LNG leak scenarios in bunkering and the gas dispersion simulation is conducted for all scenarios. At this point, the representative value of a leak size should be assigned for each leak size category. As an example, it is recommended that the maximum value is assigned for each category to derive a conservative design like as 3 mm for the minor case (1-3 mm), 10 mm for the small case (3-10 mm), 50 mm for the medium case (10-50 mm), 150 mm for the large case (50-150 mm) and full diameter for the rupture case.

(d) As the results of the simulation, the maximum gas dispersion footprint of each leak scenario is derived as a specific level of LFL concentration (variable D_n in Table 3) around the bunkering location and this value is substituted with the contribution factor of each leak scenario (variable E_n in Table 3) using Eq. (2). This step means that the hybrid method considers the probability of each scenario and the safe zone layout is modelled by reflecting their contributions to the total probability of LNG release.

(e) Finally, the safe zone boundary is derived with the sum of factored footprint values as Eq. (3) (variable F in Table 3). Based on the hybrid approach, the safe zone layout in LNG bunkering can be designed as a circle area with a radius of the calculated safe zone boundary and this value can vary with the specific level of LFL concentration based on the pre-defined design criteria (100 %, 50 % or other concentration levels of LFL).

Table 3. Variables for application of the hybrid method

No.	A	B_n	C_n	D_n	E_n	F
	Leak size	Leak frequency (/year)	Contribution factor (%)	Maximum footprint (m)	Substituted value (m)	Safety zone boundary (m)
1	Minor	B_1	C_1	D_1	E_1	F (radius)
2	Small	B_2	C_2	D_2	E_2	
3	Medium	B_3	C_3	D_3	E_3	
4	Large	B_4	C_4	D_4	E_4	
5	Rupture	B_5	C_5	D_5	E_5	

$$C_i = (B_i) \div \sum_i^n (B_i) \qquad \text{Equation (1)}$$

$$E_i = C_i \times D_i \qquad \text{Equation (2)}$$

$$\text{Safety zone boundary, F} = \sum_i^n (E_i) \qquad \text{Equation (3)}$$

Table 4. Release frequencies of the process steel pipes by diameter (per meter year)

Leak hole range (mm)	Dia. 50 mm	Dia. 150 mm	***Dia. 300 mm***	Dia. 450 mm
1 to 3	5.5E−05	2.6E−05	***2.3E−05***	2.3E−05
3 to 10	1.8E−05	8.5E−06	***7.6E−06***	7.5E−06
10 to 50	7.0E−06	2.7E−06	***2.4E−06***	2.4E−06
50 to 150	0.0E+00	6.0E−07	***3.7E−07***	3.6E−07
> 150	0.0E+00	0.0E+00	***1.7E−07***	1.7E−07
Total	8.0E−05	3.8E−05	***3.3E−05***	3.3E−05

The derived safe zone represents a potentially dangerous area due to flammable gas concentration in LNG bunkering and the goal of the hybrid approach is to reflect the reality, i.e., probability of leak occurrence in the design of the safe zone layout. In the next chapter, the application of the hybrid method is explained via an example design of the safe zone layout.

4. Example Design of the Safety Zone in Truck-to-Ship Bunkering

4.1 Scenario selection

The safe zone layouts in LNG bunkering are designed using deterministic and hybrid approaches and the purpose is to suggest a solution for the existing issue in the deterministic approach (scenario selection) by i) introducing an appropriate usage of the deterministic approach and ii) providing a complete solution, the hybrid method. As an example design of the safe zone, truck-to-ship bunkering, i.e., LNG transfer between a tank lorry and a demanding ship is considered in this study. Although the standard types of bunkering include not only ground-based bunkering (shore-to-ship and truck-to-ship) but sea-based bunkering (ship-to-ship), they may have a difference during their detail operations and thereby, the safe zone should be differently designed for each type of bunkering operation. This study is only focusing on the ground-based bunkering, especially for truck-to-ship bunkering which is the simplest energy transfer method in various industries.

An imaginary LNG-fueled ship, 60,000 deadweight (DWT) class bulk carrier is assumed as the bunkering target and the LNG is transferred from a tank lorry truck having a capacity of 15 ton for LNG supplying. It is supposed that the fuel tank of the ship has a capacity of 800 m^3 for LNG containment and 20 trucks are needed to complete the operation. Table 5 indicates the characteristics of target bunkering and it is assumed that this operation satisfies the requirements of the ISO guidelines (ISO, 2015).

Table 5. Information of the target bunkering operation

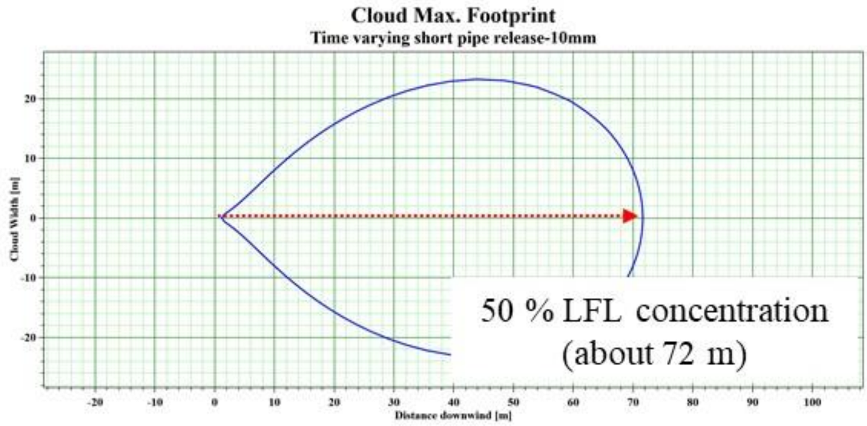
Bunkering Type	Truck to ship
Supplying facility - Tank capacity - Tank condition (LNG)	Tank lorry truck - 15 ton (LNG containment) - 6 barg & 160 deg.C
Demand facility - Tank capacity	90,000 DWT dual fueled bulk carrier - 800 m^3 IMO type-C tank
LNG transfer line - Transfer rate	40A piping line (20 m length) - Maximum 10 ton per hour

Failure of the transfer line is considered for LNG leakage scenarios and a leak point is assumed as close to the tank lorry which is the starting point of LNG loading. A leak point may vary along transfer lines and the boundary of safe zone layout will differ slightly with the selected leak point due to decreasing pressure and LNG discharge rate along the lines. It is assumed that the ESD system can be activated by automatic or manual handling and ESD valves are closed in 10 s after LNG release. Therefore, the initial leak rate is determined with the process condition of the LNG transfer line but after ESD activation, LNG is released in association of the pressure equivalence between inside and outside piping.

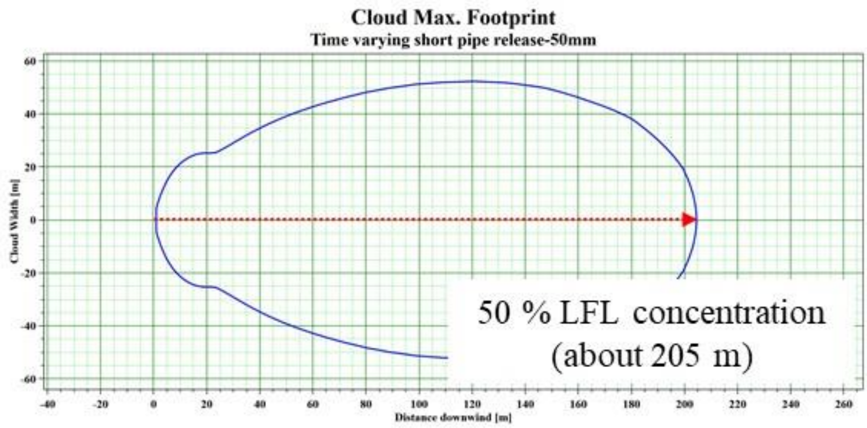
Using the DNV GL Phast, the results of LNG discharge, evaporation and dispersion are simulated (DNV GL, 2020) and the safe zone layout is projected on the imaginary map of LNG bunkering site. For simplicity of the dispersion simulation, an environment is modeled as the fixed condition i.e., ambient temperature (20 deg.C), low wind speed (1 m/s) and others atmospheric variables are set to single value in contrast to the risk-based approach or the general QRA methodology which may consider various environmental conditions with their probability to calculate associated risk factors (CMPT, 1999; Paik, 2019; Vinnem, 2014). It should be noted that this study sets the design criteria of the safe zone layout as 50 % level of LFL concentration as the security zone of the safe zone concept but 100 % level of LFL concentration is also suggested as an informative result on the safety zone of the safe zone concept (ISO, 2015; SGMF, 2018).

4.2 Application of deterministic approach

As mentioned earlier, defining a representative leak scenario is the biggest issue in application of the deterministic approach. Figure 7 shows an example of gas dispersion simulations (DNV GL, 2020) with two different LNG leak scenarios consisting of 10 mm and 50 mm leak sizes.



(a) 10 mm leak size



(b) 50 mm leak size

Figure 7. Different results of the gas dispersion simulation based on applied leak hole sizes

The balloon shaped, blue lines in Fig. 7 (a) and (b) indicate the maximum footprint of 50 % level LFL concentration from LNG release and this figure shows that the resulted safe zone boundary can tremendously differ with selected scenario. This may imply that setting an appropriate leak size is the most important point of the deterministic approach. Regarding to this, the SGMF (2018) develops the “BASiL” model to design the safe zone layout in LNG bunkering as the standard application of the deterministic approach and this recommends taking 6 % size of diameter of LNG transfer line as a credible leak size for the representative scenario. The SGMF introduces a lack of valuable statistical data relevant to the failure of the LNG system and addresses that the recommended guideline is applicable based on the limited experimental data on LNG systems and existing statistics of the process accident in the offshore industry. Also, the SGMF suggests that assuming a comparatively small size leak during LNG bunkering is reasonable with consideration for the latest technology of bunkering equipment and safety systems. Table 6 shows the SGMF recommendation on the credible leak size in relation to the diameter of LNG transfer lines.

Table 6. Possible leak sizes of metal and composite hoses in LNG transfer

Piping diameter	Hole size (mm)
2 inch / 50 mm	3
3 inch / 75 mm	4.5
4 inch / 100 mm	6
6 inch / 150 mm	9
8 inch / 200 mm	12
10 inch / 250 mm	15

Following the SGMF recommendation, 6 mm leak which is 6 % size of a diameter of the transfer line in the target bunkering (about 100 mm) is selected as the representative scenario in this example safe zone design. Environmental and other relevant variables are input in the Phast simulation and LNG discharge, evaporation and dispersion are simulated following a specific LNG release direction. As the result, 50 and 100 % LFL concentration levels are plotted in blue and red colored circles around the bunkering location as Fig. 8 and these are directly interpreted as the boundary of safety and security zones in the target bunkering. Blue and red colored ellipses represent the maximum footprint of 50 and 100 % level of LFL concentration along the specific leak direction and colored circles indicate the possible impacted areas of both LFL concentration levels which are derived with the relevant leak direction and its rotation for 360 degrees, i.e., all horizontal directions of LNG release. Following the design criteria in this study, the safe zone layout is designated as the circle area in diameter of 70 m around the bunkering site (security zone) and all personnel should be informed of the bunkering operation and their access and activities will be strictly controlled.

Figure 8. Expected safe zone layouts resulted in the deterministic approach

4.3 Application of the hybrid approach

In the hybrid approach, possible LNG release scenarios are selected with several leak hole sizes and their release frequencies are considered with the statistics of historical process accidents. For convenience of this study, the data is achieved from the International Association of Oil & Gas Producers (IOGP) which has been widely used for the offshore QRA (IOGP, 2010). It should be noted that the IOGP data provides the release frequency of process piping for 50, 150, 300, 450, 600 and 900 mm in diameters, i.e., the reference data does not perfectly correspond to the target transfer line (100 mm in diameter) and thereby the leak frequency data for a diameter of 150 mm piping replaces the data for a diameter of 100 mm piping in this example study. Table 7 provides all variables for application of the hybrid method to design the security zone layout of the target bunkering and the detail usage of this method can be achieved in the chapter 3 of this paper.

Based on the target transfer line and the IOGP data, four leak categories are defined as minor (1-3 mm), small (3-10 mm), medium (10-50 mm) and large (50-150 mm) leak cases and their frequencies are identified. Here, the rupture case is excluded because the transfer line consists of piping in a diameter of 100 mm, i.e. there is not any bigger sizes than 100 mm in this case. For the conservative approach, the maximum values of leak categories are selected as the representative sizes (3, 10, 50 and 100 mm) and those are considered as possible LNG leak scenarios in bunkering. Contribution factors are calculated in association with leak frequencies of each leak scenario.

Using the Phast software, the gas dispersion is simulated for defined scenarios and the maximum footprints of each scenario are resulted as the distance of 50 % level of LFL concentration. Figure 9 presents the result of the Phast simulation which indicates boundaries of 50 and 100 % levels of LFL concentration for each scenario.

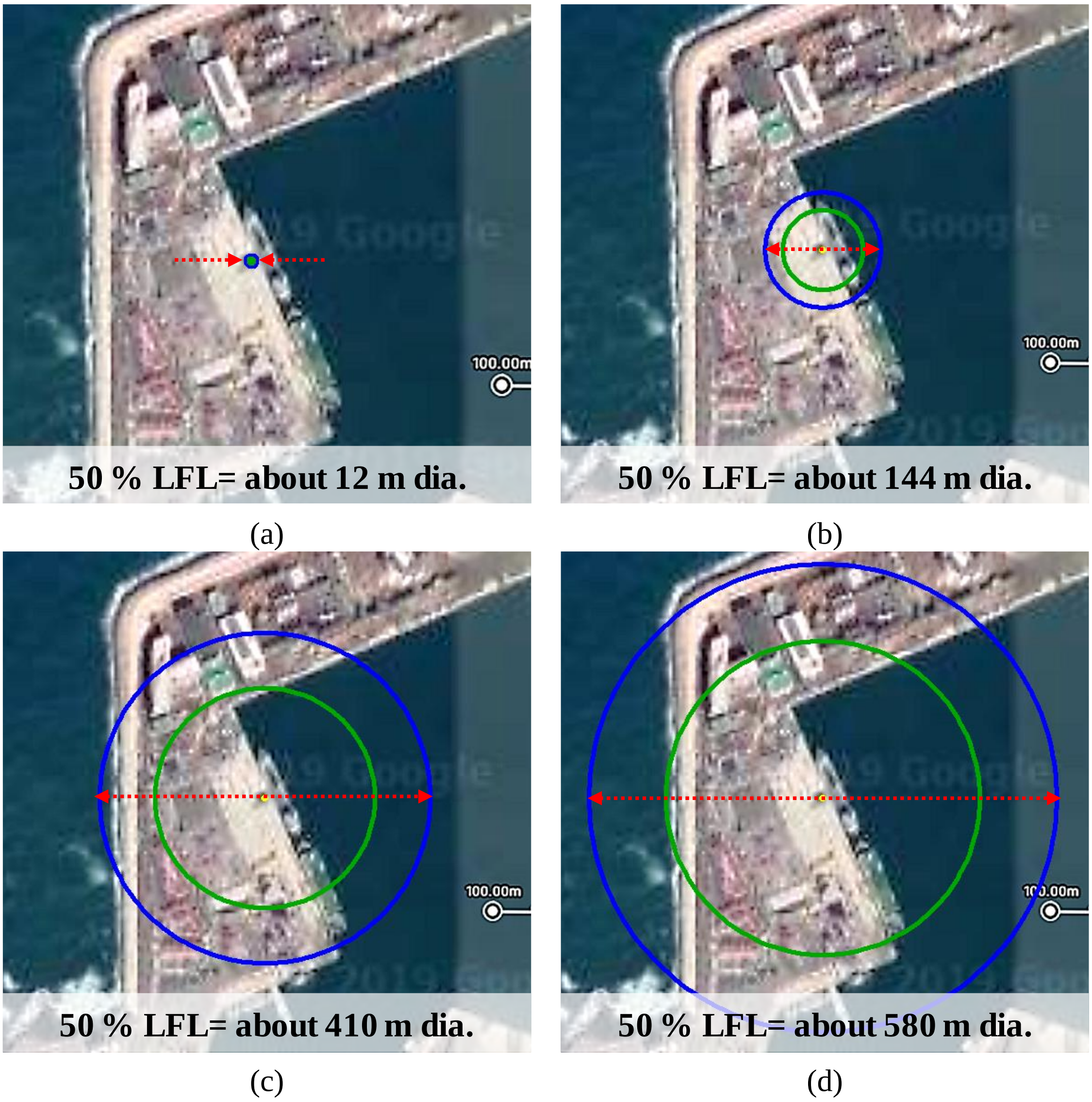


Figure 9. Boundaries of 50 and 100 % levels of LFL concentration for each LNG leak scenario

The maximum footprint value of each scenario is substituted with the pre-calculated contribution factor of each scenario and a radius of the safe zone boundary is resulted with the summation of all substituted values. As the results, the safe zone of the target bunkering is designed with the circle area in a radius of 40 m as the security zone and this area should be controlled to guarantee the minimum safety in bunkering. It is noteworthy that the hybrid approach can be flexible in its application by adjusting different variables in Tables 4 and 7. For example, selecting different statistical data (leak size, frequency, etc.) and setting different criteria for the representative size of each leak category can make a big change in the resulted safe zone.

Table 7. Leak sizes and relevant frequencies of the target bunkering line

Leak size range	Leak size (scenario)	Leak frequency	Contribution factor	Maximum footprint	Substituted value	Safe zone boundary
1 to 3 mm	3 mm	5.2E−04	68.78 %	5.93 m	4.1 m	About **40 m** (radius)
3 to 10 mm	10 mm	1.7E−04	22.49 %	71.61 m	16.1 m	
10 to 50 mm	50 mm	5.4E−05	7.14 %	204.46 m	14.6 m	
50 to 150 mm	100 mm	1.2E−05	1.59 %	289.64 m	4.6 m	
> 150 mm	None	-	-	-	-	

4.4 Discussions

Table 8 indicates the resulted safe zone layouts using deterministic and hybrid approaches. As it happens, both approaches derived similar safe zone boundaries for the target LNG bunkering.

Table 8. Required security zone in the target LNG bunkering operation.

Deterministic approach	Hybrid approach
Circle in diameter of 70 m	Circle in diameter of 80 m

In case of the deterministic approach, the representative scenario was made with the LNG leak size recommended by the SGMF (2018). Because the gas dispersion simulation and the resulted safe zone design can vary with the selected representative scenario, a reasonable leak size should be designated in the deterministic approach. In this context, the authors recommends utilizing the SGMF data instead of selecting any leak sizes by oneself unless it can make a common understanding. The SGMF is one of well-known associations in the LNG industry and its database has been widely accessed in various LNG operations. The usage of the SGMF recommendation may help to avoid a debate on the leak scenario selection and add a higher reliability on resulted safe zone layout in the deterministic approach. But this approach is still too prescriptive and deterministic and thereby more reasonable approaches are need to be developed with risk-based or probabilistic approaches.

Meanwhile, in the hybrid approach several possible leak scenarios were considered with their probability of occurrence and the safe zone was designed with the contribution of each scenario to the total probability of LNG release. This method tried to prepare a reason on selected leak sizes and scenarios by imitating the frequency analysis which is the probabilistic approach of the QRA and this can be utilized as a good example for the standard design of the safe zone layout in LNG bunkering. Some controversy may exist due to the origin of the statistical data used to define leak sizes and frequencies of LNG release. The statistics of the historical process accident usually come from the offshore industry and this data may not be directly applied on the LNG system. However, as mentioned earlier, useful data for the LNG system is not organized yet and some researches may justify the usage of the offshore data in the hybrid method as one of the probabilistic design approach on the LNG system (Davies and Fort, 2013; Park et al., 2019; SGMF, 2018; Spouge, 2015).

5. Concluding Remarks and Future Works

This paper introduced the concept of the safe zone design in LNG bunkering and suggested a way of the practical design methods, focusing on truck-to-ship bunkering, i.e., the LNG transfer between a tank lorry and a LNG-fueled ship. Based on the results of this study, the following conclusions can be made.

(1) The safe zone layout should be defined for LNG bunkering and this can be done with two industrial design methodologies, named as deterministic and risk-based approaches. Both have pros and cons in application and this paper dealt with the deterministic approach as sequential work to the author's previous research on the risk-based approach.

(2) The deterministic approach has a limitation for its practical application in association with the selection of the credible LNG leak scenario. Based on the selected leak size, the resulted gas dispersed area may differ and a quite different boundary of the safe zone can be designed.

(3) As the practical usage of the deterministic approach, this study suggested to prepare the technical background on the leak size selection and the SGMF's recommendation was referred as the valid resource. The SGMF introduces that a leak size of 6 % in diameter of the LNG transfer line is appropriate and the representative LNG release scenario in bunkering can be made with that size of leak from the transfer lines in the deterministic approach.

(4) As an alternative solution to the deterministic approach, this study proposed the hybrid method as the fusion of deterministic and risk-based approaches. This approach intends to consider all possible LNG leak scenarios in bunkering and to derive the reasonable safe zone layout by considering the contribution factor of each leak scenario to the total probability of the leak occurrence.

(5) The hybrid method adopts the statistics of historical process accident to define the credible leak scenarios like as the frequency analysis of the risk-based approach and the QRA. A criticism may exist due to the origin of the data source which mostly come from other industries. In regard to this issue, there is an imperative for the LNG industry to accumulate the dedicated statistical data

and this may contribute to more practical usage of risk-based or probabilistic design approaches on the LNG systems.

The benefits of the hybrid method is to prepare the reasonable LNG leak scenario in bunkering and to result a consensus on the resulted safe zone design. Because the concept of the safe zone in LNG bunkering and its design methodologies are not standardized and generalized yet, it is expected that this paper may help someone get an idea of their engineering solutions especially when they consider the deterministic approach for their safe zone design.

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