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Study of FSRU-LNGC System Based on a Quantitative Multi-cluster Risk Informed Model

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Abstract

The offshore LNG terminal, referred to as LNG floating storage unit or floating storage and re-gasification unit (FSRU), performs well on both building process and operation process. The LNG FSRU is a cost-effective and time efficient solution for LNG transferring in the offshore area, and it brings minimal impacts to the surrounding environment as well. This paper proposed a systematic method to integrate chemical process safety with maritime safety analysis. The evaluation network was adopted to process a comparison study between two possible locations for LNG offshore FSRU. This research divided the whole process into three parts, beginning with the LNG Carrier navigating in the inbound channel, the berthing operation and ending with the completion of LNG transferring operation. The preferred location is determined by simultaneously evaluating navigation safety, berthing safety and LNG transferring safety objectives based on the quantitative multi-cluster network multi-attribute decision analysis (QMNMDA) method. The maritime safety analysis, including navigational process and berthing process, was simulated by LNG ship simulator and analyzed by statistical tools; evaluation scale for maritime safety analysis were determined by analyzing data from ninety experts. The chemical process safety simulation was employed to LNG transferring events such as connection hose rupture, flange failure by the consequence simulation tool. Two scenarios, *i.e.*, worst case scenario and maximum credible scenario, were taken into consideration by inputting different data of evaluating parameters. The QMNMDA method transformed the evaluation criteria to one comparable unit, safety utility value, to evaluate the different alternatives. Based on the final value of the simulation, the preferred location can be determined, and the mitigation measures were presented accordingly.

Keywords: LNG floating storage and regasification unit; Quantitative multi-cluster network multi-attribute decision analysis; Maritime safety; Chemical process safety

Nomenclature

AHP	Analytic Hierarchy Process
APF	Average Possibility of Fatality
BLEVE	Boiling Liquid Expanding Vapor Explosion
FSRU	Floating Storage and Re-gasification Unit
LNGC	Liquefied Natural Gas Carrier
MADA	Multi-Attribute Decision Analysis
MCS	Maximum Credible Scenario
PLL	Potential Loss of Life
QMFMDA	Quantitative Multi-hierarchy Framework Multi-attribute Decision Analysis
RPT	Rapid Phase Transition
SUV	Safety Utility Value
UKC	Under Keel Clearance
VCE	Vapor Cloud Explosion
WCS	Worst Case Scenario

Symbol

a: The average time interval of position checks by deck officers
b: A coefficient that represents the extent of damage to a ship's hull
B_1, B_2: Breadth of Ship 1 and Ship 2
C: The width of the channel
D: Average distance between ships
D_e: Diameter of collision avoidance
D_i: Collision diameter
d: The width of channel
F: Threatened Level
f: Lateral distribution of the ship routes, often normal distribution
$f()$: The actual traffic distribution of ships
H: Depth of the channel
k_{RR}: Risk reduction factor, usually taken 0.5
L: Average vessel length
N_1, N_2: Number of ship 1, 2 passing per year
P: The probability that a vessel is involved in a collision accident during its voyage passing one assigned water area
P_c: Causation probability
P_g: Geometrical probability, collision probability without aversive measures are made.
P_x: Ship collision probability
Q_j: Number of movements of ship class j per unit time, named as traffic volume
R: Radius of Turning Circle
T: Ship's stopping distance
V: Speed of passing vessel
V_{ij}: Relative velocity
V_{rel}: Relative speed
V_1, V_2: Speed of Ship 1 and Ship 2
X, Actual length of path for one ship
Z: Distance from the centerline of the fairway
$1/r$: Distance decay curve
ρ: Traffic density, number of ships per unit area
θ: The angle that one single ship approaching the channel with

1. Introduction

Natural gas, a green fossil fuel, is liquefied via dehydration, de-heavy hydrocarbons, and deacidified. Meanwhile, the volume of liquefied Natural Gas (LNG) is approximately equal to 1/600 of that of natural gas (GIIGNL Annual Report, 2019). The high storage efficiency, low cost, and economical long-distance transportation are the main advantages of LNG. In addition, LNG serves as a civil fuel because of its eco-friendliness (high hydrogen-carbon ratio) and high calorific value.

Currently, LNG Carrier (LNGC) is the most common tool for long-distance transportation between natural gas plants and traditional LNG terminals. Since the technique of floating production, storage, and offloading keeps developing these years, many loading and discharging modes are put into use in the offshore area. The typical LNG supply chain starts at the gas exploration plants. LNG is liquefied and stored in the export terminal; through the LNGC, LNG can be transferred to import terminal to store and to carry out re-gasification process before it is sent to downstream customers for civil or industrial utilizations (Andersson et al., 2010). A floating LNG unit can substitute the traditional export terminal, acting as a liquefaction plant and LNG storage offshore, this is called floating liquefied natural gas (FLNG). On the other side, to take the place of a traditional import LNG terminal, a technology called LNG floating storage and re-gasification unit (FSRU) was adopted to store the transferred LNG and to convert the LNG to gaseous state to meet the requirements of civil and industry utilization (Aronsson, 2012).

As shown in Figure 1, the typical LNG supply chain includes gas exploration, export terminal, LNG carrier, import terminal and pipelines. LNG FSRU, which is employed to improve working efficiency of LNG import terminal, integrates the storage function with re-gasification plant, locating in the offshore or near shore areas.

Figure 1. LNG Supply Chain

Compared with traditional LNG receiving terminals, LNG-FSRU performs better on many aspects. Building time saving: an LNG-FSRU is typically commissioned in 2 years, while an onshore LNG terminal usually takes 4-5 years; Flexible to re-location: typical LNG-FSRU systems are reconfigured by LNGCs after permission procedures, and since they still can serve as transportation tools, when the natural gas market grows, they can be relocated in another area to solve emergent supply and demand problems; Cost-effective, the investment of LNG-FSRU is usually 4 to 5 times less than that of land LNG receiving terminal (Finn, 2002).

As a new concept of LNG value chain, the research of LNG FSRU has been active in the process safety community only for several years. Schleder et al. (2011) employed fault tree analysis to carry out risk analysis of FSRU. (Martins et al., 2016) completed a detailed quantitative risk analysis study of undesired events of LNG FSRU by the consequence tool and presented the safeguard actions accordingly. Most literatures of LNG FSRU risk analysis focused on the fuzzy evaluation of the sole regasification unit from the perspective of chemical safety. However, few works have been done to consider a dynamic system for both FSRU and LNGC from a systematic point of view. Therefore, the objective of this research is to propose a safety-based model for a system of FSRU and LNGC by integrating both maritime safety and chemical process safety knowledge, and we call the defined system as FSRU-LNGC integrated system. The FSRU-LNGC system includes LNGC which is to be berthed alongside the FSRU, the FSRU itself, and the operation interaction of LNGC and FSRU. Its evaluation process starts from the LNGC entering into the inner harbor area via inbound channel and ends with the completion of LNG transferring. Three consecutive processes are involved in the research, LNGC navigation, LNGC berthing alongside the LNG FSRU and cargo transferring operation between LNGC and LNG FSRU, see Figure 2.

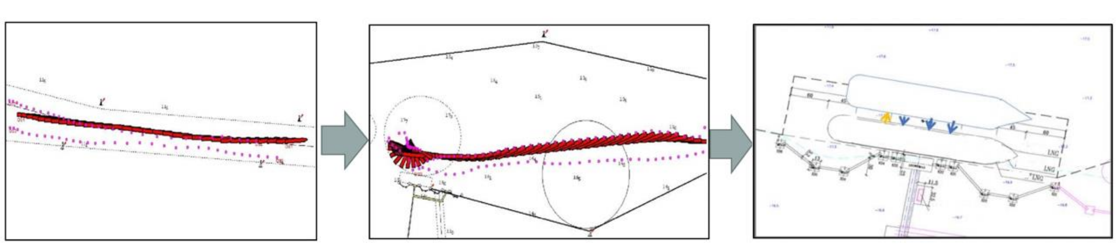

Figure 2. Defined Evaluation Processes

As shown above, the evaluation process starts with the LNGC entering the FSRU channel (navigational process), then the LNGC berthing alongside FSRU (berthing Process) and ends with the completion of LNG cargo transferring (transferring process).

A preliminary safety performance evaluation framework of the FSRU-LNGC system should be established by risk evaluation methods to build the risk model. Inspired by (Shapira and Goldenberg, 2005) and (Saaty, 1990), this study presented a quantitative multi-cluster network multi-attribute decision analysis (QMNMDA) to build a risk informed model for the defined processes of the FSRU-LNGC system. Figure 3 shows the preliminary evaluation process of the QMNMDA by incorporating the process analysis, risk assessment and attribute determination.

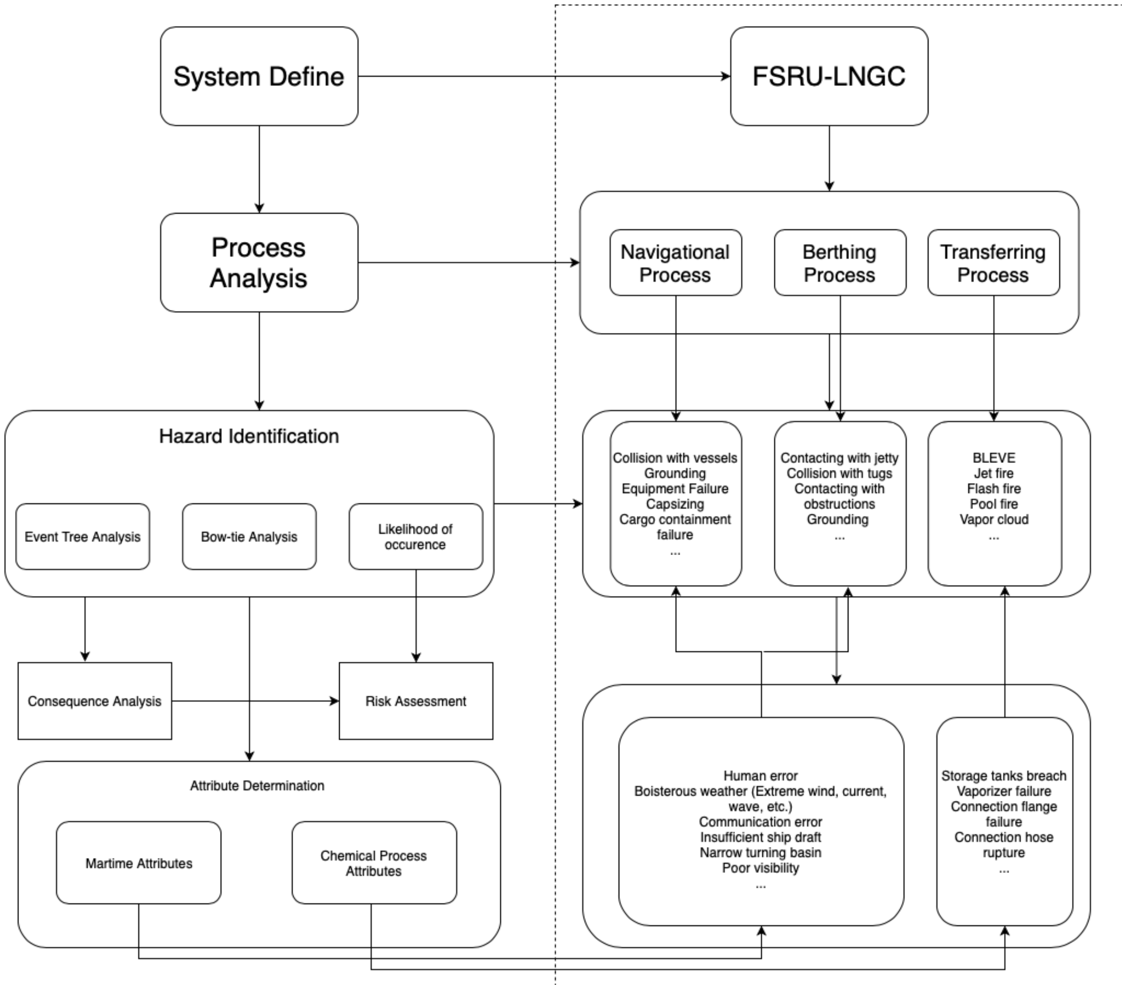

Figure 3. Proposed Evaluation Framework of QMNMDA

From the above figure, the FSRU-LNGC system will be analyzed by three processes: navigational process, berthing process and LNG cargo transferring process. Moreover, many techniques such as event tree analysis and bow-tie analysis, were adopted to identify hazards in these three processes. And the leading factors, we call attributes in the paper, of the identified hazards were categorized as maritime safety and chemical safety respectively and the corresponding attribute pools were established by detailed ship simulator study and chemical consequence analysis. The scope of this paper is restricted to operation safety of between FSRU and LNGC from a systematic safety view. Following the preliminary evaluation framework, this FSRU-LNGC study firstly analyzes the merits and demerits of relevant hazardous models for maritime safety and employs bow-tie and event-tree analysis for defined scenarios of FSRU LNGC interface. Then the ship simulator study, statistical analysis and chemical consequence analysis are carried out to build the quantitative multi-cluster model. At last, a case study of two proposed locations was adopted to investigate the safety level of FSRU LNGC systems using the model.

2. Relevant works

To establish the LNG-FSRU evaluation criteria, several factors, such as hydrographic information, navigation safety, fire and explosive risks, exclusion areas, and environment sensitivity, should be taken into consideration individually. Combined with previously recorded incidents, the most threatening hazards, collision, grounding, fire/explosion, and spillage during cargo handling, were identified by (Woodward and Pitblado, 2010)(Ji et al., 2017).

As for collision model, specifically, Fujii et al. (1974) and his group firstly proposed a model to calculate the average number of evasive actions by one ship navigating in one area. The prediction variables of his model were traffic density, diameter of collision avoidance, speed of passing vessel and relative speed. Moreover, the range of diameter of collision avoidance made the prediction values quite conservative. Macduff's model (Macduff, 1974) focused on the probable collision model, which was predicted by the geometrical probability and the causation probability. But the value of the geometrical probability will be overestimated when the angle between ship and channel is small. To determine the geometrical probability P_g, Pedersen (1995) presented a model under a two-channel situation. Channel 1 and channel 2 are assumed as two crossing channels. This model is reasonable for crossing scenario to estimate the geometrical probability due to a more practical assumption. However, the lack of ship movement data made it difficult to determine the probability distribution of ship motion. The summary of above mentioned three collision models was listed in the Table 1.

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Table 1. Summary of Ship Collision Model

Model	Expression	Drawbacks
Fujii's Model	$N = \int_{entrance}^{exit} (\rho D_e V_{rel}/V)\, dx$	De is conservative (9.5 to 16.3 times ship length), so Pg is overestimated.
Macduff's Model	$Pg = \frac{X \cdot \bar{L}}{D^2} \cdot \frac{\mathrm{Sin}(\theta/2)}{925}$	Pg is overestimated when ɵ is small and underestimated because of the assumption of two ships are equal speed.
Pedersen's Model	$P_{\Delta t} = \frac{Q_j^{(2)}}{V_j^{(2)}} f_j^2(z_j) D_{ij} V_{ij} dz_j \Delta t$	Applicable for crossing channel situation, assume ship lateral motion as normal distribution, not very accurate for head on situation

In order to precisely simulate the head on situation in the real world, the COWI model (COWI, 2008) is applied to calculate ship collision probability.

$$Px = Pt \times Pg \times Pc \times k_{RR} = LN_1N_2 \left|\frac{V_1 - V_2}{V_1V_2}\right| \times \left(\frac{B_1 + B_2}{c}\right) \times (3 \times 10^{-4}) \times k_{RR} \qquad (1)$$

Compared to other models, the COWI model considered the risk mitigation measure and reduced the uncertainty in some extent by assuming ship motion as normal distribution. Moreover, the most likelihood situation for LNGC navigation in inbound channel is head-on situation, so the COWI model was adopted to carry out simulation for LNGC navigation safety phase. It is widely accepted that visibility is a key factor to influence coastal navigation and the leeway and drift angle, which was deemed as a significant parameter to show the vessel's maneuverability, was largely dependent on the magnitude of wind and current. Therefore, the main parameters to evaluate the collision hazard are determined as wind, visibility and the probability of following current.

On the other hand, Fujii et al. (1998) proposed his grounding model by establishing the relationship between the expected number of groundings and the predictors (causation probability, ship's speed, traffic density and shoal width). Meanwhile, Macduff (1974) adopted Buffon's needle problem to estimate Pg, the geometrical probability, and the major predictors are channel width and stopping distance of ships. These two above-mentioned models are only affected by the ship particulars while other elements related to location are set to be constant. The uncertainties of the real navigation situation are ignored in most cases, and this model merely considered historical accident data. Simonsen (1997) developed their model to estimate the expected annual number of groundings with the number of transshipments per year, the average time interval of position checks by deck officers and the transverse coordinates of shoals.

Table 2 serves as a review of above-mentioned grounding models, illustrating their expressions and drawbacks.

Table 2. Summary of Ship Grounding Model

Model	Expression	Drawbacks
Fujii's Model	$N_G = P_C D_\rho V$	Human factors, ship's maneuverability and environmental aspects were all neglected.
Macduff's Model	$P_g = \frac{4T}{\pi C}$	Causation probabilities are unknown; this model cannot recommend any risk control option. Traffic density is assumed uniformly.
Simonsen's model	$\sum_{\text{Ship class i}}^{\text{n class}} P_{C,i} Q_i e^{-C/a_i} \int_{z_{min}}^{z_{max}} f_i(z)dz$	Human factors and ship maneuverability are still neglected and effect of traffic (Q) and ship class (i) are not evidence based.

To overcome those above-mentioned drawbacks, Montewka et al. (2011) have proposed a more accurate grounding model with the consideration of the maneuverability of an individual ship and the properties of the traffic. In addition, Automatic Information System was employed to determine the distribution of the ship's motion.

$$F = M \times \frac{UKC}{H \times r} = \frac{R \times b}{d \times s \times c} \times \frac{UKC}{H \times r} \quad (2)$$

For the LNGC navigation process, the Montewka's Model was selected as the one to simulate stranding situations since it has a better interpretation and has considered ship maneuverability. Based on the above equation, the main parameters selected for grounding hazard of navigational process are channel width, channel curvature and under keel clearance.

When berthing or unberthing operation is taking place, the LNGC shows a characteristic of low speed and large drift angle (Yang, 1996). Typically, berthing operation for large ships should consider factors such as temperature, berthing ability, wind force, visibility and thunderstorm, and Bai (2010) presented the berthing influence factors as tug assistance, wind, current, longitudinal speed control, transverse speed control and angular velocity control . What is more, poor communication between crew and marine pilots during berthing operation will probably lead to marine disasters near ports, and the language and cultural diversity of seafarers needs to be considered as well (Winbow, 2002). To evaluate this complicated operation process in a quantitative way, Yang (Yang, 1996) proposed a berthing model by presenting models of ship, propeller and rudder individually and he took full considerations of interactions between each part. Yang set up a two-coordinate system, one is fixed coordinate, and the other is ship moving coordinate system. Based on Yang's theory, the LNG ship simulator was employed to perform a high-precision simulation for LNGC berthing. This simulator adopted a six-freedom motion mathematical model proposed by Zhang's research group (Zhang et al., 2007) and integrated wind disturbing force models and wave force models as the keys for external force. To evaluate the LNGC berthing operation, six main parameters were determined as, water depth of turning basin, following current speed, berth length, radius of turning area, transverse wave height and the probability of crossing wind (beam wind).

After the berthing process is completed, the LNG should be transferred from LNGC to LNG FSRU, which is a typical Ship-to-Ship LNG transferring process. Two common solutions for Ship to Ship transferring process exist, one is called side-by-side transferring pattern, and the other is called tandem transferring pattern (Liu et al., 2001). There are three liquid transferring connection hoses and one vapor counter flow connection hose. For the LNG FSRU system, many causes would result in LNG accidental release such as FSRU or LNGC tank breach, connection pipe rupture and LNG vaporizer failure. These may be the result of collision, faulty operation, bad maintenance, or be caused by a whole variety of primary low severity events, such as small igniting leaks, due to maintenance or other operations, *e.g.*, at the regasification unit in which LNG is heated. Hence, in such cases secondary devastating major events are domino effects of the much less severe primary ones. Furthermore, possible associated consequence phenomena of LNGC release on water have been identified (Abbasi et al., 2010; Li et al., 2012) as Boiling Liquid Expanding Vapor Explosion (BLEVE), vapor cloud explosion (VCE), jet fire, cloud flash fire, pool fire, rapid phase transformation, cryogenic burns, *etc*. Figure 4 shows a simplified bow-tie diagram for LNG accidental release to consider both the causes and the outputs of the top event. The sequence in which these phenomena are mentioned is quite opposite to the likelihood in which they can occur. For example, in principle a BLEVE or a VCE cannot be excluded although these phenomena never have been directly observed. However, the nature of the hydrocarbon makes it possible just as if it is LPG, although less likely than LPG. BLEVE could occur if a sustained fire heats one of the tanks and the pressure relief valve would not be able to cope with the evaporation rate as happened once with an LNG loaded tank truck in Spain (Planas et al., 2015). VCE of a natural gas cloud cannot be excluded as well; in a massive cloud once ignited and meeting obstacles fast flame generated blast is possible, while even transition of the deflagration into detonation (DDT) with much stronger blast cannot be excluded. For ethane and other fuels these phenomena of DDT are observed on so-called large-scale in experiments (*e.g.,* Pekalski et al., 2014), which compared to most accidental releases in size should be considered small-scale, while the propensity to DDT of various hydrocarbons, including methane, the main component of natural gas, can be predicted

(Saif et al., 2017). However, the likelihood of the other above mentioned phenomena given a release is much higher. Rapid phase transition explosions occur when methane under certain conditions is spilled on water; but their blast is weak.

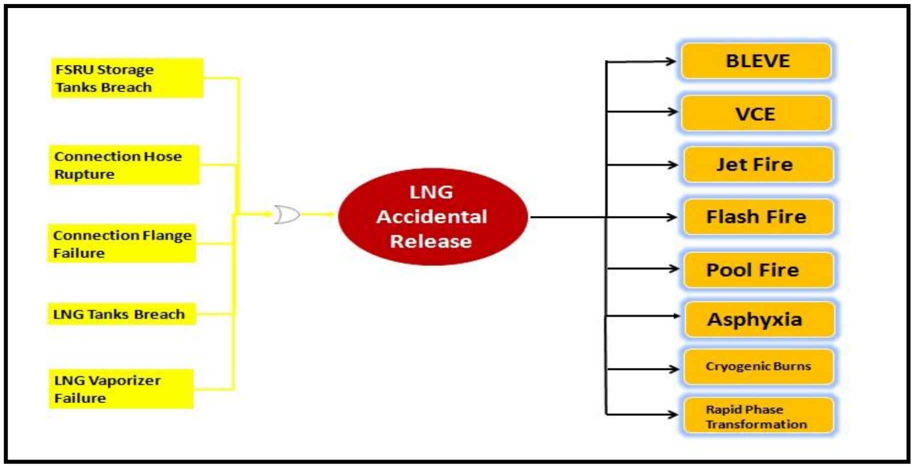

Figure 4. Simplified Bow-tie Diagram for LNG Accidental Release

As shown in above simplified bow-tie diagram, five primary causes may result in LNG accidental release for the FSRU-LNGC system: FSRU storage tank breach, connection hose rupture, connection flange failure, LNGC Tank breach and LNG vaporizer failure. Frequency of domino effects may be much greater. When LNG is released under the waterline, it will boil vehemently and convert to vapor bubble, then the LNG bubble may escape above the waterline to produce LNG vapor. For above-waterline release, jet fire, cloud flash fire and pool fire may form under different scenarios. Since a vapor cloud explosion is not likely to occur over the open water area (Hightower et al., 2004), the possible fatality related consequences taken into account here are flash fire, pool fire and jet fire, while the BLEVE, and vapor cloud are deemed as less likely consequences. Then, the flammable calculations including fireballs (instantaneous releases), jet fires (pressurized releases), pool fires (after liquid spills evaporation), and vapor cloud fires or explosion are processed based on the unified dispersion model (UDM), which is part of the DNV-GL PHAST software package.

3. Model development

Based on values and criteria there are quite a few techniques to assist a decision maker. Utility theory is a quantitative approach for decision makers to value a wide range of feasible alternatives, and it is good at finding a better solution by calculating the final utility value. Multi-attribute decision analysis (MADA) is an optimizing decision-making method to get the output of overall utility function, which is constituted by weight vectors multiplied by utility values. Based on the calculated overall utility value of each alternative, the preferred decision can be made with the maximum expected utility value (Keeney and Raiffa, 1993). In addition, opposite to AHP (Analytic Hierarchy Process), the Analytic Network Process (ANP) has a nonlinear structure and does not require independence among elements in different hierarchies. Saaty (1990) pointed out that the network of ANP is built by clusters which incorporate decision parameters. The network structure in ANP is represented in two forms, one is a graphical form and the other is a matrix form. The graphical form qualitatively represents the interaction relationship and feedback relationship between the various components that make up the network, while the matrix form quantitatively represents the degree or magnitude of interaction or feedback.

Since MADA is good at dealing with the decision-making problems among several attributes in one layer, and ANP outperforms for a case with the overall determination of different layers as here is required for the maritime and the spill risk determination. By combining these two approaches, this research developed MADA and ANP into a quantitative multi-cluster network multi-attribute decision analysis (QMNMDA). The core idea of this method is to divide the top problem into several processes first, then different processes are evaluated individually by various quantitative tools, such as risk simulation software, ship simulator and data analysis software. Next, the major hazards are identified under corresponding processes. To quantitatively evaluate different hazards, previous theories and equations may be referred to determine the major attributes which are under the hazard cluster. By considering the data availability, the risk attribute clusters can still go down to sub factor clusters to quantitatively evaluate the top object directly. Generally, QMNMDA has two aspects, one is the construction of the network, and the other is the calculation of the weight values of the ANP elements. In order to construct the structure of the problem, all the interrelationships between the elements should be well considered. When an element in one cluster depends on another, the relationship is represented by an arrow within a cluster. All of these relationships are calculated using pairwise comparisons and a supermatrix, containing the influences between elements. The ultimate power of the supermatrix is to calculate the overall weight, which is determined by a fuzzy analytic network process (F-ANP) approach. Then the risk evaluation utility value is to be determined by the Delphi method and statistical analysis. At last, the risk category is obtained based on the principle of maximum membership. Put simply, the framework determination of QMNMDA is a top-to-bottom work, and then the final evaluation is progressing bottom-to-top.

(1) Preliminary network of QMNMDA

Following the working flow as shown in Figure 3, the graphical form ANP based cluster model was established to determine the safety level for LNG FSRU locations. By evaluating operation process, hazard identification and characteristics of locations, the preferred location can be determined through the outputs of the clusters and elements, see Figure 5.

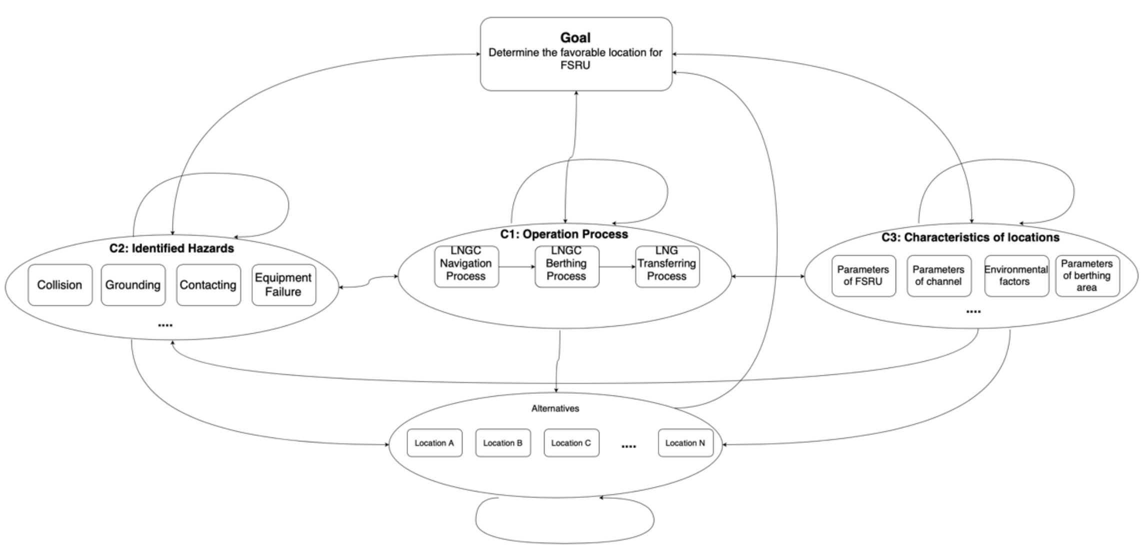

Figure 5. Preliminary network for QMNMDA model

As Figure 5 shows, the set of alternatives and evaluation factors for the evaluation objective are determined and the relationships of different elements have been established. Three operation processes have dependent relations while the relationships between any two elements in C2 and C3 are deemed as independent.

As shown in Figure 5 in the operational process there are three sub-processes. For the navigation process, the hazards are identified as collision, grounding, equipment failure, capsizing and cargo containment failure. For the berthing process, the hazards are identified as the LNGC contacting with jetty and obstructions, collision with tugs and LNG grounding due to insufficient UKC. In addition, the bow-tie diagram Figure 4 tells the possible hazards for the transferring process and that of the LNG vaporizer failure (re-gasification), being FSRU storage tanks breach, connection hose rupture, LNG tanks breach and connection flange failure.

(2) Weight calculation

Next, the F-ANP approach is employed to calculate the weight values of the three processes. This is because no historical data exist and no overall simulation is possible, hence experts have to be interviewed about the weight of the various contributing hazards. Replies of different experts will vary and will be merged into fuzzy triangle numbers. The definition of fuzzy triangle number proposed by (Chang, 1996) was presented to deal with the calculation process of overall weight values [0, 1]. The fuzzy triangle number p of evaluation set U, $U = (u_1, u_2, u_3, \ldots, u_n)$, is defined as $\mathrm{p} = (\mathrm{l}, \mathrm{m}, \mathrm{s})$, and $0 \leq \mathrm{l} \leq \mathrm{m} \leq \mathrm{s} \leq 1$, its membership function is μ(x).

$$\mu(\mathrm{x}) = \begin{Bmatrix} \frac{x-l}{m-l}, & x \epsilon (l, m] \\ \frac{s-x}{s-m}, & x \epsilon (m, s] \\ 0, & otherwise \end{Bmatrix} \tag{3}$$

where *l* and *s* stand for the lower and upper value, respectively, and *m* stands for the most probable value of $p \ \epsilon \ [0,1]$. While $\mathrm{l} = \mathrm{m} = \mathrm{s}$, p is deemed as a nonfuzzy number. Then the fuzzy triangle number based fuzzy judgement matrix can be constructed by pairwise comparisons, shown in Equation 4.

$$\mathrm{p} = \begin{pmatrix} p_{11} & p_{12} & \cdots & p_{1n_1} \\ p_{21} & p_{22} & \cdots & p_{2n_1} \\ \vdots & \vdots & \ddots & \vdots \\ p_{n_1 1} & p_{n_1 2} & \cdots & p_{n_1 n_1} \end{pmatrix} \tag{4}$$

Where $p_{11} = p_{22} = \cdots = p_{n_1 n_1} = (0.5, 0.5, 0.5)$. p_{ij} is defined as the complementary judgment matrix for the fuzzy triangle number p, and p_{ij} is effective only when it satisfies the consistency test. In the work presented by Saaty (1990), the eigenvalue approach was proposed.

Next, the partial weight value matrix of the general supermatrix can be determined by the equation.

$$W_{11}^{(1i)'} = (d'(u_{11}), d'(u_{12}), \ldots, d'(u_{1i}), \ldots, d'(u_{n_i}))^T \tag{5}$$

$$d'(u_{1i}) = \min \mathrm{V}(C_{1i} \geq C_{1k}, C_{1h}) \tag{6}$$

After normalization, equation 5 is converted to

$$W_{11}^{(1i)} = (d \quad (u_{11}), d \quad (u_{12}), \dots, d \quad (u_{1i}), \dots, d \quad (u_{n_i}))^T \tag{7}$$

The comprehensive importance of component $u_{1i}(i = 1,2, \dots, n_1)$ is defined as C_{1i}.

$$C_{1i} = \sum_{j=1}^{n_1} p_{ij} \otimes \left(\sum_{i=1}^{n_1} \sum_{j=1}^{n_1} p_{ij}\right)^{-1} \tag{8}$$

$\mathrm{V}(C_{1i} \geq C_{1k})$ is applied to calculate the probable weight when $C_{1i} \geq C_{1k}$ is true.

$$\mathrm{V}(C_{1i} \geq C_{1k}) = \left\{\begin{array}{cc} 1, & m_{ij}^{1i} \geq m_{ij}^{1k} \\ \frac{s_{ij}^{1i} - l_{ij}^{1k}}{s_{ij}^{1i} - l_{ij}^{1k} + m_{ij}^{1k} - m_{ij}^{1i}}, & m_{ij}^{1i} < m_{ij}^{1k} \ and \ l_{ij}^{1k} \leq s_{ij}^{1i} \\ 0, & otherwise \end{array}\right\} \tag{9}$$

where $\mathrm{i} = 1,2, \dots, n_i;\ k = 1,2, \dots, n_1$ & $k \neq i; j = 1,2, \dots, n_1$

Then W_{11} can be obtained by repeating these procedures n_1 times.

$$W_{11} = (W_{11}^{(11)}, W_{11}^{(12)}, \dots, W_{11}^{(1i)}, \dots, W_{11}^{(1n_i)})^T \tag{10}$$

At last, the matrix form of ANP, supermatrix $W_{ij}(i, j = 1,2, \dots, N)$ is determined after similar processes to get $W_{22}, W_{33}, \dots, W_{n_1 n_1}$.

$$\mathrm{W} = \begin{array}{cc} & \begin{array}{ccccccccccc} & C_1 & & & C_2 & & \cdots & & C_N & \\ d(u_{11}) & d(u_{12}) \cdots & d(u_{1n_1}) & d(u_{21}) & d(u_{22}) \cdots & d(u_{2n_2}) & & d(u_{N1}) & d(u_{N2}) \cdots & d(u_{Nn_N}) \end{array} \\ \begin{array}{cc} C_1 & \begin{array}{c} d(u_{11}) \\ d(u_{12}) \\ \vdots \\ d(u_{1n_1}) \end{array} \\ C_2 & \begin{array}{c} d(u_{21}) \\ d(u_{22}) \\ \vdots \\ d(u_{2n_2}) \end{array} \\ & \vdots \\ \vdots & \\ C_N & \begin{array}{c} d(u_{N1}) \\ d(u_{N2}) \\ \vdots \\ d(u_{Nn_N}) \end{array} \end{array} & \begin{bmatrix} W_{11} & W_{12} & \cdots & W_{1n_1} \\ W_{21} & W_{22} & \cdots & W_{1n_2} \\ \vdots & \vdots & \cdots & \vdots \\ W_{N1} & W_{N2} & \cdots & W_{Nn_N} \end{bmatrix} \end{array} \tag{11}$$

Following the weight value determination procedures, the weight values of process layer are calculated as below.

$$\mathrm{p} = \begin{array}{c} \\ k_{NP} \\ k_{BP} \\ k_{TP} \end{array} \begin{array}{c} \begin{array}{ccc} k_{NP} & k_{BP} & k_{TP} \end{array} \\ \begin{pmatrix} (0.5, 0.5, 0.5) & (0.4, 0.4, 0.5) & (0.2,0.3,0.4) \\ (0.5, 0.6, 0.6) & (0.5, 0.5, 0.5) & (0.2, 0.4, 0.5) \\ (0.6, 0.7, 0.8) & (0.5, 0.6, 0.8) & (0.5, 0.5, 0.5) \end{pmatrix} \end{array} \tag{12}$$

By calculating the comprehensive importance of component and probability when $C_{1i} \geq C_{1k}$ is true, the normalized weight value matrix of the process layer is:

$$k_p = (0.137, 0.321, 0.542)^T \tag{13}$$

(3) Final network of FSRU-LNGC system.

By repeating the weight value determination process for the hazard layer, the following Table 3 is made up from the collected data of our FSRU risk analysis group, illustrating the overall weight value of the identified hazards for the three processes.

Table 3. Overall Weight Values of the Identified Hazards for the Three Processes

Operation Process	Weight Value with Dependencies	Identified Hazards	Priority within the Process via ANP	Overall Priority
Navigation Process	0.137	Collision	0.581	0.0796
		Grounding	0.356	0.0488
		Equipment Failure	0.032	$4.4*10^{-3}$
		Capsizing	0.002	$2.74*10^{-4}$
		Cargo Containment Failure	0.029	$3.97*10^{-3}$
Berthing Process	0.321	Contacting with Jetty	0.621	0.201
		Collision with Tugs	0.064	0.0205
		Contacting with Obstructions	0.223	0.0716
		Grounding	0.092	0.0499
Transferring Process	0.542	Flash Fire	0.503	0.2726
		Pool Fire	0.212	0.1149
		RPT	0.096	0.05203
		BLEVE	0.001	$5.42*10^{-4}$
		Jet Fire	0.122	0.06612
		VCE	0.066	0.03577

As shown above, the priority scores within each process served as indicators to determine the major hazards of the three processes. This paper neglected the hazards with a priority value of priority score under 0.1. Therefore, collision and grounding were determined as the major hazards for the navigation process, while contacting with jetty and contacting with other obstructions were those for the berthing process, and flash fire, pool fire and jet fire were identified for the LNG transferring process.

Then the ship simulator DMU V-dragon 3000A was adopted to find the attributes for the maritime processes, *i.e.*, navigation process and berthing process. Extreme conditions were selected as the input parameters: the wind direction was blowing to the shore; the radius of turning area was set as 500 meter and 1000 meter, respectively; the berthing length was set as 1.2 times and 2 times ship's length overall. Two scenarios were designed to determine the most influential factors:

1. Full loaded, port side berthing with spring tidal current;
2. Full loaded, starboard side berthing with ebbing tidal current.

The failure simulation runs were shown in Table 4.

Table 4. Simulation Results of Ship Simulator for Berthing Process

Number of runs	Wind	Current	Radius of Turning Area	Water Depth	Transverse Wave Height	Berth Length	Consequence
1	N-6	Spring, 0.6m/s	500m	20m	0.7m	2L	Contacting the FSRU
2	N-6	Spring, 1.5m/s	1000m	21m	0.8m	2L	Contacting the jetty nearby
3	N-8	Spring, 0.8m/s	1000m	21m	1.0m	2L	Contacting the FSRU, tugs malfunction
4	N-6	Spring, 0.6m/s	1000m	19m	1.5m	2L	Contacting the berthing ship nearby
5	N-8	Ebb, 0.9m/s	1000m	20m	0.8m	2L	Contacting the FSRU, tugs malfunction
6	N-7	Ebb, 0.7m/s	1000m	15m	0.8m	2L	Contacting with the berth nearby
7	N-6	Ebb, 0.6m/s	1000m	20m	0.7m	1.2L	Contacting with FSRU, failed to get alongside the berth
8	N-6	Spring, 0.6m/s	1000m	20m	0.8m	1.2L	Contacting with FSRU, failed to get alongside the berth

Based on the simulation results by the ship simulator, the most significant parameters leading to collision of LNGC are poor visibility, beam wind frequency and large current; leading factors for grounding are insufficient UKC, inadequate channel width and sharp channel curvature. The magnitude of following current, transverse wave height and water depth of berthing area are the major attributes for contacting with the nearest obstruction; while the attributes for contacting between LNGC and LNG FSRU are berth length, radius of turning basin area and the probability of crossing wind.

For LNG transferring process, the connection flange failure and connection hose failure were identified as major attributes for the identified fires based on the collected data. By considering the correlations and mutual dependency, the final evaluation network is determined, shown as Figure 6.

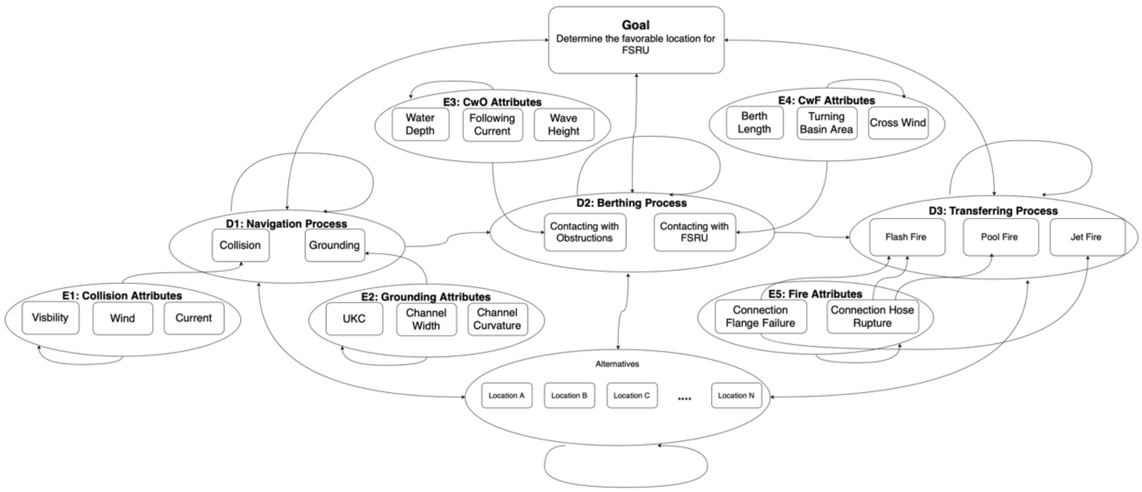

Figure 6. FSRU-LNGC System Evaluation Network of QMNMDA

From Figure 6, we can see that the three processes are set as independent but each of them has dependent elements, and the E level lists the leading factors to the identified events of the D level.

(4) Attribute utility value determination

To analyze the safety performance of proposed FSRU LNGC system, the five scale set is predetermined as V, $V = (v_1, v_2, v_3, v_4, v_5) =$ (favorable, acceptable, moderate, limited acceptable, unacceptable). In order to determine the utility value of each attribute, the FSRU-LNGC risk analysis group must establish an evaluation scale. The group was made up with 30 senior officers of deck department aboard ships, 30 professional pilots and 30 professors from maritime colleges. Based on the opinions of the expert judgment team and previous studies on the marine maneuvering, every individual attribute was evaluated quantitatively based on the safety utility value (SUV) or risk tolerance index, which was distributed evenly from 0 to 1 with the interval of 0.2. Furthermore, safety utility value range from 0.8 to 1.0 means the environment of this location is favorable to locate LNG FSRU, while the value locating between 0.6 and 0.8 means it is acceptable for LNG FSRU; the range 0.4 to 0.6 means moderate environmental conditions for the system; limited acceptable when the SUV is in the range of 0.2 to 0.4; it is unacceptable when the utility value goes below 0.2. The evaluation standards for adopted attributes of navigational and berthing process were established based on the collected questionnaires (see Appendix 1). The total evaluation standards were displayed in the Table 5 by analyzing the collected data for all the attributes of navigational process and berthing process.

Table 5. Evaluation Standard for Each Attribute of Maritime Safety Study

Utility Range / Factors	*Favorable, (0.8,1]*	*Acceptable, (0.6,0.8)*	*Moderate, (0.4,0.6]*	*Limited Acceptable, (0.2,0.4]*	*Unacceptable, [0,0.2]*
Visibility (d/y)	＜15	15～20	20～30	30～40	＞40
Windy Days (d/y)	＜30	30～60	60～100	100～150	＞150
Following Current Prob.	< 3%	3~6%	6~10%	10~15%	>15%
Channel Width	>900	650~900	450~650	300~450	< 300
Channel Curvature	<15°	15°~25°	25°~35°	35°~45°	>45°
UKC	>15m	10~15m	5~10m	2~5m	<2m
Water Depth	>25m	22~25m	18~22m	15~18m	<15m
Following Current	<0.3m/s	0.3~0.6	0.6~0.8	0.8~1	>1m/s
Wave Height	＜0.3m	0.3～0.6	0.6～1.0	1.0～1.2	＞1.2m
Berth Length	>2.5L	2~2.5L	1.5~2L	1.2~1.5L	<1.2L
Turning Basin Area	>1200m	1000~1200 m	800~1000 m	600~800 m	<600m
Cross Wind Prob.	< 1.5%	1.5~3%	3~4.5%	4.5~6.5%	>6.5%

The data collected by the Delphi approach are utilized to establish the evaluation standard, and then the utility value function of E-level elements in Figure 6 are able to be established by statistical tools, see Appendix 2; next, the real observation data and the boundary value of evaluation scale may be used to determine the utility value for the attribute layer. Multiplying the utility values by the corresponding weight factors, the overall utility value for FSRU LNGC system is obtained by the following function.

$$Overall\ Utility\ Value = k_{NP}\sum_{i} w_i A_{NP} + k_{BP}\sum_{j} w_j A_{BP} + k_{TP}\sum_{k} w_k A_{TP}$$

Where k_{NP}, k_{BP}, k_{TP} stand for the weight values of each process, w_i, w_j, w_k are defined as sub-weight factors of each attribute, and A_{NP}, A_{BP}, A_{TP} are described as the utility value of each attribute of navigation process, berthing process and transferring process.

4. Case Study

To assess the safety extent of FSRU-LNGC systems, two locations were applied to carry out case study based on the proposed model. The proposed LNG FSRU for Location A is at the south edge of the coast line and at a near shore area; while the proposed Location B is at the northeast side of the coast line, and at an offshore area, 2300 meters extended from the shoreline. The proposed direction of Location A is 053°～233°, berth length is 446 meters (m); the design direction of Location B is 099°～279° and berth length is 430 m. After the dimension of two proposed locations were determined, the evaluation steps can be processed from LNGC navigating in the inbound channel to the LNG successfully transferring from LNGC to FSRU.

4.1 Maritime Processes

Besides the proposed locations of FSRU-LNGC systems, a common LNGC type, Q-Flex, is applied in this study as the input ship type of the ship simulator by considering the current trend for LNG offshore application, and the dimension of its receiving unit FSRU is predetermined accordingly (Bowen et al., 2008), see Table 6.

Table 6. Parameters of LNGC and FSRU

Parameters	LNGC(Q-Flex)	FSRU
LOA	303	315
Loading Capacity	142933.7 m^3	217000 m^3
Breadth	50	50
Draft	12	12.5

At the left side of the bowtie shown in Figure 4 five scenarios are presented. From those we shall consider here only the flange and hose ruptures. The LNGC or FSRU LNG tank rupture will occur only after a collision incident, where the probability will be a fraction of the collision probability depending on collision speed and location of collision. It will be difficult to estimate the probability with any accuracy, but the frequency may be lower than 10^{-6}/yr, hence rather unlikely. On the other hand, very large LNG clouds resulting from a gaping hole in a tank may travel as a heavy gas over a distance of say 2 kms. In case of delayed ignition, it is not sure what will happen, flash fire or VCE. There remains the re-gasification unit. There is at least one typical accident known on a peak shaving plant that occurred in 2014, at which maintenance work at the unit resulted in an explosion propelling a fragment toward a tank and perforating the wall (Rukke, 2016). Also, here it will be difficult to estimate a failure frequency rate.

Generally, the loading / unloading equipment of FSRU have four liquid loading hoses and two vapor return hoses, each of them has one spare part. Referred from 20, the maximum loading capacity, length of LNG loading hoses and other parameters are listed in Table 7 (Nafta, 2015).

Table 7. Parameters of FSRU's Loading Equipment

Parameter	Value
Maximum Loading Capacity	8000 m^3/h for all loading hoses
Maximum Unloading Capacity	5000 m^3/h for all loading hoses
Number of LNG Loading Hoses	4 (1 spare)
Number of Vapor Return Hoses	2 (1 spare)
Inner Diameter of LNG Loading Hoses	0.254 m
Length for LNG Loading Hoses	18.5 m
Inner Diameter of LNG Loading Hose Flange	0.41 m
Inner Diameter of Vapor Return Hose Flange	0.41 m

Considering the data availability for attributes of collision hazard, the visibility parameter is determined by number of days under poor visibility (visible distance < 4000 m) per year; the wind parameter is determined by number of days under standard wind scale, which is equal to number of days under Beaufort scale 6 and 7 plus 1.5 times number of days under Beaufort scale 8 or more (Ji et al., 2014); and the parameter current is determined by the probability of following current, which is the most difficult situation for ship maneuvering. For grounding hazard, the attribute channel width and channel curvature can be determined directly by the actual channel data, and the minimum under keel clearance (UKC) is equal to the minimum chart water depth minus actual draft of LNGC. For the second process, berthing process simulation, the water depth for the contacting possibility for LNGC and other navigation obstruction is the minimum water depth in berthing area; "Following Current" is the magnitude of following current during berthing operation; while the transverse wave height can be directly obtained from the hydrographic data of two harbor authorities. For the hazard of possible collision with FSRU, the berth length and turning basin area is the values of designed berth length and radius of turning water, and the crossing wind, which is defined as the wind blowing the LNGC toward FSRU side, was evaluated by the wind rose maps of two locations. Therefore, the actual values of navigation process and berthing process related attributes for two alternatives are shown in Table 8. Then the utility values of navigation process and berthing process are calculated by maximum membership functions integrating evaluation scale in Table 6.

Table 8. Values of Maritime Processes Related Attributes for Two Locations

	Channel Width	Channel Curvature	UKC	Windy Days	Following Current Prob.	Visibility	Water Depth	Following Current	Wave Height	Berth Length	Turning Area Radius	Crossing Wind Prob.
Location A	1050m	31°	12m	140	7.6%	22	20 m	0.8m/s	1.08 m	1.5L	1020m	4.6%
Location B	690 m	27°	5m	151	9.3%	30	17m	0.85m/s	0.81 m	1.25L	1260m	3.8%

4.2 LNG Transferring Process

Based on the previous research (D'alessandro et al., 2016; Pitblado et al., 2006), it is a reasonable to simulate this event "LNG releasing on the water" by two scenarios: one is called maximum credible scenario (MCS), which is defined as: an accident that is within the realm of possibility (i.e., probability higher than 1×10^{-6}/yr) and has a propensity to cause significant damage (at least one fatality) (Khan, 2001).; another one is called worst case scenario (WCS), which means the extremely dangerous situation for FSRU LNGC system.

For the two scenarios, the external environment factors for weather data input, wind, air temperature and relative humidity, can be obtained from the meteorological and hydrographic records of two locations, and the input data for MCS and WCS are listed in Table 9.

Table 9. Input Data for Simulation Plans

	Wind	**Air Temperature**	**Humidity**	**Pasquill Stability**	**Estimated Release Volume**	**Hole Size Diameter**
Maximum Credible Scenario (MCS)	Prevailing Wind (A; 8 m/s, N; B:6.7m/s, NE)	Yearly Average (A: 10.5℃; B:15.1℃)	Yearly Average Humidity (A: 69%; B: 75%)	E	1167 m^3	0.2m (Flange Failure)/0.12m (Hose Rupture)
Worst Case Scenario (WCS)	15m/s (A: SE; B: NE)	Highest Monthly Average Temperature (A: 15.1℃; B: 20.6℃)	Highest Monthly Average Humidity (A: 83%; B: 88%)	Loc. A: C; Loc. B: D	2667m^3	0.41 m (Flange Failure)/0.254 m (Hose Rupture)

For maximum credible scenario, the input parameter "wind" was the prevailing wind for two locations. As shown in Figure 9, the wind rose map of location A shows the prevailing wind direction was north wind with the speed of 8 m/s; while the prevailing wind direction of location B is northeast wind with the speed of 6.7 m/s; the air temperature for MCS was the average temperature of one whole year, where 10.5 degree centigrade for location A and 15.1℃ for location B; similarly, the humidity parameter was selected as the average humidity for a whole year, 69% for location A and 75% for Location B.

For worst case scenario, the "wind" parameter was the most hazardous when the wind is blowing toward the pier since the fire may get more assets and people involved. By considering the wind rose map of each location, the most hazardous wind directions were southeast and northeast for location A and location B, respectively and the worst wind speed is 15m/s because it is the maximum speed to allow LNG transferring operation under Chinese regulations (JTS 165-5-2016). Since the air temperature may fluctuate day to day, the WCS air temperature was chosen as the highest monthly average one for a whole year, 15.1℃ for location A and 20.6℃ for location B.

Similarly, the humidity parameter was determined as the highest monthly average humidity for a whole year, 83% for location A and 88% for location B.
The release preconditions, hose loading capacity, leakage time and hole size, were determined as the main parameters to define the exact releasing volume of MCS and WCS. For WCS, the hose loading capacity was referred as the LNG FSRU's maximum loading capacity and the accidental release time was determined as 20 minutes to calculate the simulated release volume for the events as connection hose rupture and flange failure. As shown in Table 5, the inner diameter of LNG loading hose and loading hose flange were 0.254 m and 0.41 m, respectively, so the hole size was determined as the total-damage scenario. For MCS, the hose capacity was determined as the 87% of the maximum loading capacity and the release time was 10 minutes; the holes were determined as 0.2 m for connection flange failure and 0.12 m for connection hose rupture scenario.

The runs were designed in 4 group comparisons with 8 simulations by DNV-GL PHAST software, shown in Table 10. Simulation plan 1, 2, 3 and 4 were taken for connection flange failure. Among these four simulation plans, simulation plan 1 and 2 took place in location A under scenario MCS and WCS, respectively; Simulation plan 3 and 4 took place in location B under scenario MCS and WCS. Meanwhile, simulation runs 5 to 8 were for connection hose rupture, and simulation plan 5 and 6 took place in location A under scenario MCS and WCS; Simulation plan 7 and 8 took place in location B under scenario MCS and WCS, respectively.

Table 10. Outcomes of Designed Simulation Plans

Plan	Location	Scenario	Dia. of Hole Size (mm)	Est. Leakage Volume	Fire Type	Thermal Radiation Distance (m)			Flammability Limits Distance (m)		
						$4kW/m^2$	$12.5kW/m^2$	$37.5kW/m^2$	UFL	LFL	0.5LFL
1	A	MCS	200	1167	Flash				220	794	1590
2	A	WCS	410	2667	Jet	1141	1022	976			
3	B	MCS	200	1167	Flash				194	771	1546
4	B	WCS	410	2667	Jet	1128	1016	976			
5	A	MCS	120	1167	Flash				11	77	277
6	A	WCS	254	2667	Pool	501	302	192			
7	B	MCS	120	1167	Flash				9	70	202
8	B	WCS	254	2667	Pool	722	525	222			

Figure 7 shows the preliminary simulation outputs for two alternatives under the condition of “flange failure with worst case scenario” (simulation plan 2 and 4).

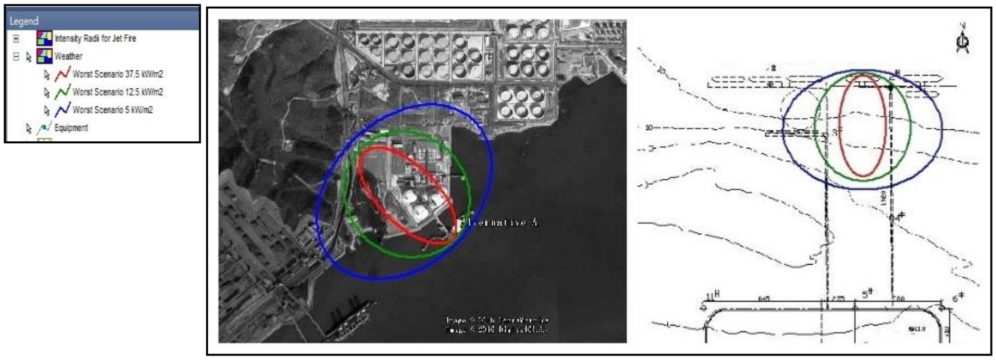

Figure 7. Simulation Outputs for Two Alternatives under WCS for Event A

From Figure 7, on the ***left*** is the simulated thermal radiation influence areas of location A and on the ***right*** that of location B. The red circle is the high thermal radiation area with heat flux 37.5 kW/ m^2, the green one is the thermal radiation intensity of 12.5 kW/c and the blue circle is the range of thermal radiation intensity of 5kW/m^2. Meanwhile, other simulation plans were taken under different input data, and Table 11 shows all simulated outcomes of eight simulation plans. The potential fatalities would be calculated based on the values of thermal radiation distance and flammability limits distance.

4.3 Results and discussions

After the completion of simulation runs for three processes, the utility value should be determined from bottom hierarchy to the top. Navigational process and berthing process, which were called maritime safety study in this research, adopted risk evaluation matrix to determine each utility value; while for chemical process safety part, LNG transferring process was determined by the potential loss of life (PLL), which given the population density is in principle the integral of the societal risk incidents presented as components of the so-called $F–N$ -curve ($PLL = \sum_{i=1}^{n} f_i N_i$). PLL is expressed in fatalities/year; the metric is also called Expected Value (EV) (Hirst and Carter, 2002) and Average Rate of Death (RoD) (CCPS, 2000).

The vulnerable building for two alternatives should be determined to calculate PPL value. Three ranges (500-meter circle, 1000-meter circle and 1500-meter circle) were drawn to show potential damaged buildings for location A and B. On the other hand, the PLL of flash fire was calculated by the distances of LFL and 0.5 LFL. The possibility of fatality was assumed 100% in Zone 1, a defined zone between UFL contour and LFL contour; and 50% for Zone 2, defined between LFL contour and 0.5 LFL contour. Referred by DNVGL MPACT Model (DNVGL, 2016), the heat flux value “4 kW/m^2” could lead to 1% possible fatality, while the value of “12.5 kW/m^2” was 50% and the value of “37.5 kW/m^2” was 100%. As for the range between these three-point values, the lethality ellipse, was employed to calculate the PLL in this study. According to the Table 10, the PLLs of location A and location B under MCS and WCS were calculated shown in below table.

Table 11. Summary of PLL for Simulation Runs

Plan	Loc.	Scenario	Fire Type	Involved Vulnerable Buildings	Potential Involved Personnel	PLL	Thermal Radiation Distance			Flammability Limits Distance		
							$4kW/m^2$	$12.5kW/m^2$	$37.5kW/m^2$	UFL	LFL	0.5LFL
1	A	MCS	Flash	Working stations (7), LNG tanks (3), residential area (1), LNG FSRU system (1), berth (2), office building (1), warehouses (3), storage tanks (15), grocery shop (1), police station (1)	Zone 1:301; Zone 2: 76	339				220	794	1590
2	A	WCS	Jet	Working stations (3), LNG tanks (3), residential area (1), berth (1), LNG FSRU system (1), office building (1)	Red Zone: 694; Blue Zone: 10; Green Zone: 15	706	1141	1022	976			
3	B	MCS	Flash	LNG FSRU system (1), berth (2), pipeline bridge (2), turning basin (1)	Zone 1:78; Zone 2: 38	97				194	771	1546
4	B	WCS	Jet	LNG FSRU system (1), berth (1), pipeline bridge (2), turning basin (1)	Red Zone: 124; Blue Zone: 15; Green Zone: 25	142	1128	1016	976			
5	A	MCS	Flash	Working stations (1), LNG tanks (1), LNG FSRU system (1)	Zone 1:14; Zone 2: 28	28				11	77	277
6	A	WCS	Pool	Working stations (1), LNG tanks (3), LNG FSRU system (1)	Red Zone: 40; Blue Zone: 20; Green Zone: 9	58	501	302	192			
7	B	MCS	Flash	LNG FSRU system (1), pipeline bridge (1)	Zone 1:14; Zone 2: 10	19				9	70	202
8	B	WCS	Pool	LNG FSRU system (1), berth (1), pipeline bridge (2), turning basin (1)	Red Zone: 32; Blue Zone: 17; Green Zone: 35	54	722	525	222			

The probability 10^{-5} per year was usually defined as the boundary of the individual risk of fatality for marine transfer operation (MARIN, 2016). The frequency of each scenario can be obtained from the event tree analysis, so the value of risk can be calculated by PLL timing frequency. Based on the ALARP boundary values (Sames and Hamann, 2009), the safety utility scale was built accordingly. By the calculated weight value of three processes, the total utility value for Location A and Location B under maximum credible scenario can be determined.

The total safety utility value for location A under MCS is:

$$SUV_A = k_{NP} \sum_i w_i A_{NP} + k_{BP} \sum_j w_j A_{BP} + k_{TP} \sum_k w_k A_{TP} = 0.4225 \quad (14)$$

The total utility value for location B under MCS is:

$$SUV_B = k_{NP} \sum_i w_i A_{NP} + k_{BP} \sum_j w_j A_{BP} + k_{TP} \sum_k w_k A_{TP} = 0.5931 \quad (15)$$

Under WCS, SUV'_A = 0.1212; SUV'_A = 0.2036.

Therefore, location B performs better than location A either under MCS or WCS. Under MCS, they both located in the moderate level, but under WCS, the safety utility value of location A and B were in the limited acceptable range. The calculated results told us the extreme external conditions should be avoided in advance to ensure the safety of the FSRU-LNGC system.

For the navigational process, location A outperformed location B on both "collision" and "grounding", proving the navigation environment of location A was more reliable for LNG carriers than that of location B; for berthing process, location B had a higher overall score, showing it was less risky for identified contacting with berthing obstructions and LNG FSRU. For LNG transferring process, two events and two scenarios were identified for LNG accidental release, location B performed better than location A on both of the two events as it separated the populated areas with two pipeline bridges so that less vulnerable buildings were involved in the vicinity of location B. Location B outperformed location A in two of three processes, and had a higher score in the total utility value since offshore FSRU is a safer solution, although offshore area usually has a less favorable navigation environmental factors.

5. Conclusion

This research serves as a quantitative way to evaluate the three consecutive processes for an integrated engineering system, FSRU-LNGC system. A QMNMDA model was presented to evaluate the process safety level of the defined system and both ship simulator and consequence analysis were employed to fulfill the research objective. In addition, a real case with two FSRU areas was taken to show the procedures of this safety analysis. During the evaluation process, some may be taken into account to mitigate the systematic risk into an acceptable level. For navigational process, the security zones, both static and dynamic zones, should be set up for large scale LNG carriers, such as Q-Flex and Q-Max, to avoid other traffic interfering LNGC, and this measure has been proved to reduce the occurrence of collision in inbound channels significantly by Ma and Wu (Ma and Wu, 1998); the recommended routes should be always top priority to navigate since the UKC can meet the requirement of safe sailing or large draft vessels may ride on the tide to pass the shallow areas. For berthing process, enough turning basin, especially enough berthing width should be ensured to lower the risk of contact with FSRU or other navigational hazards, and the transverse speed of the LNGC should be observed frequently when it is approaching the LNG FSRU. For LNG transferring process, the emergency plan and procedures should be implemented before the operation begins; the responsible officers should be assigned to ensure every possible contingency could follow an organized procedure; evacuation plans and extreme situation trainings were the key factors to succeed in potential disasters.

This study serves a trial to apply both nautical simulation and chemical process simulation on offshore industry. In the evaluation process, the objective environmental factors were evaluated via simulation and statistical software. However, human factors and other uncertainties are necessary to consider under different hydrographic and meteorological conditions for the FSRU-LNGC system. From the perspective of offshore safety, this data-driven direction would be a right way to establish evaluation scale in a more close-to-reality way. To accomplish this goal step by step, more data sources should be added to monitor LNG operations in different dimensions and more non-linear mathematical models should be applied to build a clearer relationship between raw data and safety performances for both LNGC and FSRU.

Acknowledgement
I would like to pay my highest respect to Dr. Mannan for his great contribution to make this world safer and better. His attitude towards process safety will be always memorized.

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APPENDIX 1: Sample Questionnaire for Safety Utility Value of LNG FSRU

Evaluation Attributes

Which department are you in?

1. Maritime Institute
2. Pilot Station
3. Shipping Company

How many years have you worked/researched for LNG carriers?

1. Less than 5years
2. 5 to 8 years
3. More than 8 years

The evaluation scale was set between 0 and 1, and five evaluation ranges were determined with the even interval of 0.2 based on the safety level for LNG FSRU system, see table below.

Table. 1-1 Quantitative Value for Safety Qualitative Evaluation

Favorable	Acceptable	Moderate	Limited Acceptable	Unacceptable
[0.8,1]	[0.6,0.8)	[0.4,0.6)	[0.2,0.4)	[0,0.2)

Safety utility value range from 0.8 to 1.0 means the environment of this location is favorable to build LNG FSRU, while the value locating between 0.6 and 0.8 means it is acceptable for LNG FSRU; the range 0.4 to 0.6 means moderate environmental conditions for the system; limited acceptable when the safety utility value is in the range of 0.2 to 0.4.

Safety Evaluation for "Visibility"

Visibility value for LNG carrier is defined as the number of days under poor visibility (visible distance < 4000m) per year. Now please fill the blanks about the relevant values.

Which value do you think is the most appropriate one when safety utility value of "Visibility" is set as 0.2, 0.4, 0.6 and 0.8, respectively? Please fill the blanks.

Table. 1-2 "Visibility" Evaluation Table

	Safety Utility Value= 0.2	Safety Utility Value= 0.4	Safety Utility Value= 0.6	Safety Utility Value= 0.8
Restricted Visibility Days/Yr				

APPENDIX 2: Utility Function Determination for "Visibility" by R

```
> lm.fit=lm(Risk~Vis, data=data1)
> summary(lm.fit)

Call:
lm(formula = Risk ~ Vis, data = data1)

Residuals:
     Min       1Q   Median       3Q      Max
-0.19608 -0.12252 -0.01319  0.12838  0.27082

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)  0.8303064  0.0440807   18.84   <2e-16 ***
Vis         -0.0108557  0.0009122  -11.90    7e-15 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.1407 on 41 degrees of freedom
Multiple R-squared:  0.7755,    Adjusted R-squared:   0.77
F-statistic: 141.6 on 1 and 41 DF,  p-value: 7.005e-15
```

Figure 2-1. For "Risk= $\beta_0+\beta_1$Vis"

```
> lm.fit=lm(Risk~log(Vis), data=data1)
> summary(lm.fit)

Call:
lm(formula = Risk ~ log(Vis), data = data1)

Residuals:
      Min        1Q    Median        3Q       Max
-0.115569 -0.060755 -0.001431  0.057830  0.183096

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  1.93130    0.06452   29.93   <2e-16 ***
log(Vis)    -0.43800    0.01784  -24.56   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.07494 on 41 degrees of freedom
Multiple R-squared:  0.9363,    Adjusted R-squared:  0.9348
F-statistic:   603 on 1 and 41 DF,  p-value: < 2.2e-16
```

Figure 2-2. For "Risk= $\beta_0+\beta_1$In(Vis)"

```
> summary(lm.fit)

Call:
lm(formula = Risk ~ Vis + I(Vis^2), data = data1)

Residuals:
      Min        1Q    Median        3Q       Max
-0.112369 -0.036073  0.004677  0.040416  0.143156

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)  1.251e+00  3.279e-02   38.14   <2e-16 ***
Vis         -3.495e-02  1.637e-03  -21.35   <2e-16 ***
I(Vis^2)     2.555e-04  1.694e-05   15.08   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.05511 on 40 degrees of freedom
Multiple R-squared:  0.9664,    Adjusted R-squared:  0.9647
F-statistic: 575.5 on 2 and 40 DF,  p-value: < 2.2e-16
```

Figure 2-3. For "Risk= $\beta_0+\beta_1$Vis+ β_2Vis^2"

```
> lm.fit=lm(Risk~Vis+I(Vis^2)+I(Vis^3), data=data1)
> summary(lm.fit)

Call:
lm(formula = Risk ~ Vis + I(Vis^2) + I(Vis^3), data = data1)

Residuals:
      Min        1Q    Median        3Q       Max
-0.124696 -0.009811  0.000220  0.012575  0.138456

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)  1.464e+00  4.408e-02  33.224  < 2e-16 ***
Vis         -5.504e-02  3.662e-03 -15.030  < 2e-16 ***
I(Vis^2)     7.492e-04  8.583e-05   8.729 1.04e-10 ***
I(Vis^3)    -3.441e-06  5.918e-07  -5.814 9.38e-07 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.04085 on 39 degrees of freedom
Multiple R-squared:  0.982,     Adjusted R-squared:  0.9806
F-statistic: 709.6 on 3 and 39 DF,  p-value: < 2.2e-16
```

Figure 2-4. For "Risk= $\beta_0+\beta_1$Vis+ β_2Vis^2 +β_3Vis^3"

```
> lm.fit=lm(Risk~Vis+I(Vis^2)+I(Vis^3)+I(Vis^4), data=data1)
> plot(lm.fit)
> summary(lm.fit)

Call:
lm(formula = Risk ~ Vis + I(Vis^2) + I(Vis^3) + I(Vis^4), data = data1)

Residuals:
      Min        1Q    Median        3Q       Max
-0.093642 -0.016540 -0.000006  0.018339  0.132348

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)  1.362e+00  7.141e-02  19.071  < 2e-16 ***
Vis         -4.131e-02  8.437e-03  -4.897 1.83e-05 ***
I(Vis^2)     1.870e-04  3.243e-04   0.577   0.5676
I(Vis^3)     5.337e-06  4.927e-06   1.083   0.2855
I(Vis^4)    -4.588e-08  2.557e-08  -1.794   0.0808 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.03973 on 38 degrees of freedom
Multiple R-squared:  0.9834,    Adjusted R-squared:  0.9817
F-statistic: 563.2 on 4 and 38 DF,  p-value: < 2.2e-16
```

Figure 2-5. Risk= $\beta_0+\beta_1$Vis+ β_2Vis^2+β_3Vis^3 +β_4Vis^4

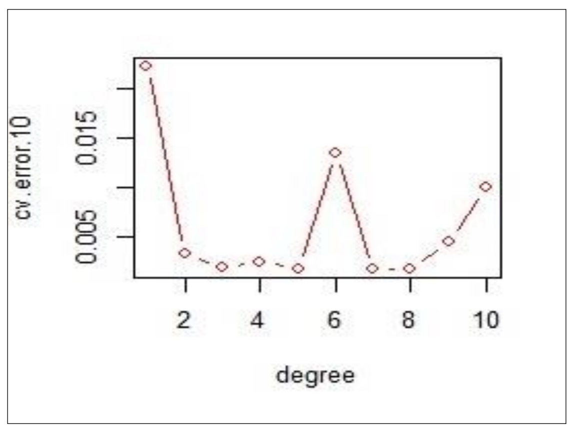

Figure 2-6. K-fold Cross Validation