Facility Layout Optimization of LNG-FSRU System

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This research presents a quantitative assessment of layout optimization of liquefied natural gas (LNG) floating storage and regasification unit (FSRU) system. Compared to other loading/unloading facilities, the LNG-FSRU system has advantages on both building and operation phases, such as cost-effectiveness, time efficiency and minimal impact to the surrounding environment. A quantitative study on the optimal facility siting has been performed for an LNG-FSRU system; safety and economic objectives are studied based on the Multi- Attribute Decision Analysis (MADA). Hazards are identified with the considerations of LNG-FSRU, LNG Carrier and management system. Analytic Hierarchy Process (AHP) is adopted in order to establish the safety performance of the LNG-FSRU system. Previous risk records are applied to determine weights of the outcomes and overall system expected utility value. Three factors - navigation safety index, operation safety index, and management index are deemed as the first hierarchy of utility function framework. In addition, sub-factors such as cryogenic risk, fire and explosion risk, ship collision risk, and stranding risk were analysed. This paper serves as a quantitative study to convert risk evaluation into five ranges of utility outputs. The proposed approach was applied to two hypothetical alternatives for LNG-FSRU infrastructure layout parameters to optimize the construction location. The maximum value of total utility function can be used for decision making.

Key Words: FSRU; MADA; Layout Optimization; Utility Function

Introduction

Liquefied natural gas (LNG) liquefied via dehydration, de-heavy hydrocarbons, and deacidified. Meanwhile, the volume of LNG is approximately equal to 1/600 of that of natural gas (Zednik, 2000). Therefore, the high storage efficiency, low cost, and economical long-distance transportation are the main advantages of LNG. In addition, LNG can be an optimized industrial and civil fuel because of its eco-friendliness and high calorific value.

Typically, LNG Carriers (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 new loading and discharging modes are put into use in offshore area. The typical LNG supply chain starts at the gas exploration plants (Henrik, 2010). 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 regasification process before it is sent to customers for civil or industrial utilizations. A floating LNG unit can substitute the traditional export terminal, acting as a liquefaction plant and LNG storage near shore. A LNG floating storage and regasification unit (LNG-FSRU) can take the place of an import terminal to store the transferred LNG and to convert the LNG to gaseous state so that customers can apply natural gas directly.

Compared with traditional LNG receiving terminals, LNG-FSRU performs better on many aspects. Time saving: an LNG-FSRU system 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, and they still can serve as a transportation tool; Cost-effective, the investment of LNG-FSRU is usually 4 to 5 times less than that of land LNG receiving terminal (Finn, 2002).

Hazard Identification

Generally, hazards are identified by HAZOP, FMECA, and What-if analysis. The typical hazards identified for an LNG-FSRU system are contact with cryogenic liquid, Pool Fire, Flash Fire, Rapid Phase Transition (RPT), Stranding, Contacting with other objects in the vicinity, and Leaking during cargo transferring (Paltrinieri, 2015).

To establish the LNG-FSRU location 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 threaten hazards, collision, stranding, fire/explosion, and spillage during cargo handling, are selected as attributes of the multi attribute decision analysis (MADA) model.

Multi - Attribute Decision Analysis

Multi – attribute decision analysis was employed to obtain the preferred decision of building one LNG FSRU system. MADA is an optimum 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 (AICHE, 1995). Analytic Hierarchy Process (AHP) was firstly proposed by Dr. Saaty in the 1970s to solve decision making problems by evaluating different factors from bottom hierarchy to the highest one. This research combines these two methods to optimize the final decision.

The objective is the first step, *i.e.*, to make a decision on the location of two hypothetical alternatives, which are located in the northern coast line and southern coast line of China. Then, the decision hierarchy should be developed to evaluate the attributes level by level from bottom to top. Furthermore, the weight vectors and utility values should be determined by calculation. The final decision can be made by analyzing the outputs of total utility values of the different alternatives accordingly.

LNG-FSRU Location Evaluation Framework

The LNG FSRU system consists of the LNG carrier (LNGC), which is to be berthed alongside the FSRU, the FSRU itself, and the management level of LNGC and FSRU. Specifically, the whole process starts from the LNGC, then enters into the inner harbour area, and ends with the completion of LNG transferring. To process MADA, the first hierarchy of attributes were determined as navigation safety, operation safety, and management level and each of them have some factors like collision, stranding, cryogenic spillage, fire/explosion, etc. Then, the sub-factors, which are located in the bottom of the hierarchy would be determined as the most influential ones to each factor above mentioned. The location evaluation framework with different hierarchies can be shown in the following Figure 1.

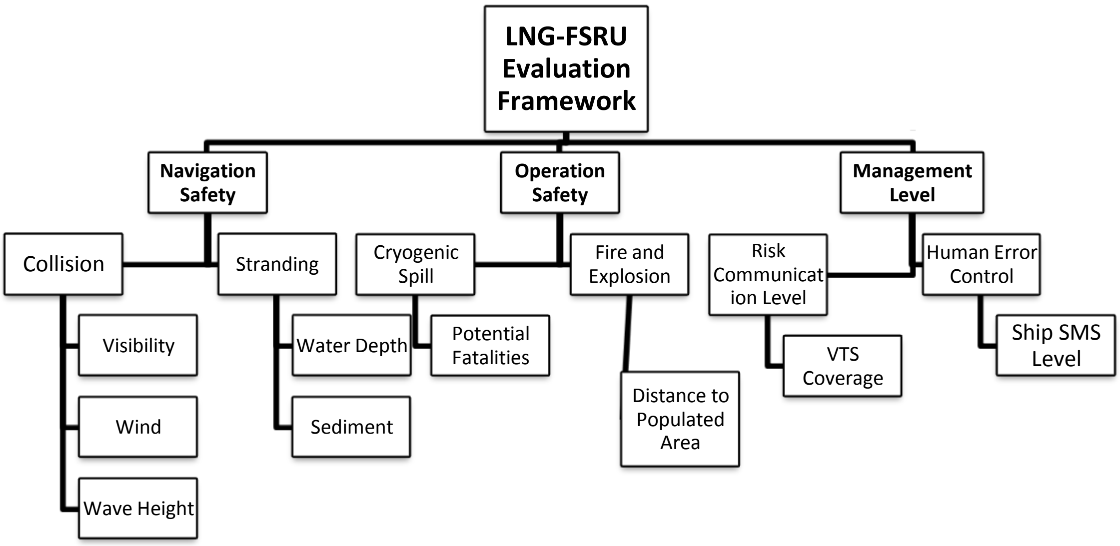

Figure 1 LNG-FSRU Location Evaluation Framework

Determination of Weight Vector

The AHP is adopted to assign values of each attribute. By applying pairwise comparison, the evaluation matrix of first hierarchy can be obtained as shown in Table 1.

Table 1 Evaluation Matrix of First Hierarchy

Evaluation Index	K_1	K_2	K_3
K_1, Navigation Safety	**1**	**1.37**	**4.35**
K_2, Operation Safety	**0.73**	**1**	**2.86**
K_3, Management Level	**0.23**	**0.35**	**1**

By calculation, the maximum eigenvalue of evaluation matrix is $\lambda_{max} = 3.0018$, and the weight vector(eigenvector) can be obtained accordingly, after normalizing, the weight vector is $W_A = (0.5146, 0.3628, 0.1226)$. Therefore, the consistency index is

$$CI = \frac{\lambda_{\max} - n}{n-1} = \frac{3.0018-3}{3-1} = 0.0009$$

Average Random Consistency Test

To measure the scale of consistency index reasonably, the Saaty's average random consistency scale, RI is introduced.

500 comparison matrixes are randomly constructed, shown as $A_1, A_2, \cdots, A_{500}$, thus 500 eigenvaule can be calculated as $CI_1, CI_2, \cdots, CI_{500}$. The value of RI is calculated by the below formula.

$$RI = \frac{CI_1 + CI_2 + \cdots CI_{500}}{500} = \frac{\dfrac{\lambda_1 + \lambda_2 + \cdots + \lambda_{500}}{500} - n}{n-1}$$

The Saaty's average random consistency scale value (Saaty, 1990), RI, is shown in Table 2.

Table 2 Average Random Consistency Scale Value

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**
RI	**0**	**0**	**0.58**	**0.90**	**1.12**	**1.24**	**1.32**

From above table, the consistency rate is shown below.

$$CR = \frac{CI}{RI} = \frac{0.0009}{0.58} = 0.00155 < 0.1$$

The output shows a satisfied consistency, thus the weight vector passes the consistency test. The weight vector for the first hierarchy is, $W_A = (K_1, K_2, K_3) = (0.5146, 0.3628, 0.1226)$

For navigation safety, the relative weight can be calculated by fatalities per year, which is shown in Table 3 (Woodward,2010).

Table 3 Potential Fatalities from LNGC Operation per ship year

Accident Category	**Fatalities per year**
Collision (Contact Included)	$5.88*10^{-3}$
Stranding	$2.93*10^{-3}$
Cryogenic Spill	$2.64*10^{-4}$
Fire/ Explosion	$6.72*10^{-4}$
Total	$9.74*10^{-3}$

Today there are 23 LNG-FSRU systems existing in the world (IGU, 2016), Table 3 shows the potential fatalities of LNG accidents of all LNG carrier operations. From the IGC world LNG report, 410 LNG carriers are serving for world trade (IGU, 2016). Therefore, the potential fatalities from LNG-FSRU accidents can be estimated accordingly, shown in Table 4.

Table 4 Estimated Fatalities of LNG FSRU per ship year

Accident Category	**Fatalities per year**
Collision (Contact Included)	$3.30*10^{-4}$
Stranding	$1.64*10^{-4}$
Cryogenic Spill	$1.48*10^{-5}$
Fire/ Explosion	$3.77*10^{-5}$
Total	$5.47*10^{-4}$

The weight vector of the first attribute, navigation safety, is determined by fatalities of collision and stranding and after normalizing the output is (0.7112, 0.2888).

Determination of Utility Value

To obtain utility values, the collision evaluation index is determined by various factors such as wind, visibility, current, and ship maneuvering parameters. External environment factors, *e.g.*, visibility, current, wave, are the major parameters to get the utility value of collision. For stranding part, the factors, water depth, tide height, and sediment material are adopted to calculate utility value of stranding.

For operation safety, the relative weights of cryogenic spill and fire/explosion are determined by the similar method as mentioned above. The weight vector of second attribute, operation safety, is calculated accordingly as (0.2819, 0.7181).

For the management level, the Vessel Traffic Service (VTS) coverage percentage and ship safety management system (SMS) level can represent risk communication level and human error control, respectively. For the SMS on board, the value can be given to five different categories so that the ship SMS can be stated quantitatively, as shown in Table 5.

Table 5 Ship Safety Management System Scale

0 = Not effective: SMS is not functional at all

1 = Limited effective: SMS is in a limited functional state

2 = Moderate: Most seafarers know the contents of SMS, infrequent training.

3 = Effective: Most seafarers can act as requirements of SMS, periodic training.

4 = Highly effective: All seafarers are very familiar with SMS; strictly comply with requirements of SMS.

Establishment of Evaluation Scale

In order to establish the relationship between expected utility value and risk level, five qualitative evaluation scales (favorable, acceptable, moderate, limited acceptable, and unacceptable) are converted to five utility ranges evenly.

The boundary values of impact factors are determined by various regulations and standards. Visibility: Number of days under poor visibility (visible distance < 4000m) per year; Wind: Beaufort scale 6 as standard wind scale. Number of standard wind scale = No. of days (Scale 6 and 7) + 1.5*No. of days (> scale 7) (Ji, 2014) ;Wave: Maximum wave height in sea areas of the proposed project; Water depth: Minimum water depth point in inbound channel and operation areas; Sediment material: different material to reflect the damage extent in case of stranding; Potential fatalities: Estimated fatalities per year once cryogenic spill and fire/explosion accidents happen, for natural hazards, historically less than 10^{-6}, for unacceptable risk, usually near or above 10^{-3} (Shortreed, et al, 1995); Distance to populated areas: Minimum distance from the operation area to the closest populated area; VTS coverage: Percentage of areas covered in the inbound channel and operation areas; Ship SMS level: The scale can be determined as shown in table. Therefore, the evaluation scale of different factors is shown below.

Table 6 Evaluation Scale of Impact Factors

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**
Wind (d/y)	**＜30**	**30～60**	**60～100**	**100～150**	**＞150**
Wave (m)	**＜0.5**	**0.5～2**	**2～4**	**4～6**	**＞6**
Water Depth(ft)	**>69**	**59~69**	**49~59**	**39~49**	**< 39**
Sediment Material	**Sand**	**Mixture of Sand and Mud**	**Mud**	**Clay**	**Rock**
Potential Fatalities	$<10^{-6}$	10^{-5}~10^{-6}	10^{-4}~10^{-5}	10^{-3}~10^{-4}	$>10^{-3}$
Distance to Populated areas (ft)	**>5000**	**3000~5000**	**2000~3000**	**1000~2000**	**<1000**
VTS Coverage (%)	**＞96**	**96～90**	**90～80**	**80～70**	**＜70**
Ship SMS Level	**4**	**3**	**2**	**1**	**0**

Decision Making Process

Two locations, Alternative A located in 38°57'23"N, 121°53'11" and Alternative B located in 32°32'50"N, 121°25'35"E, are adopted to carry out the decision making process of LNG-FSRU system, the data is abstracted from author's previous study, formal safety assessment (FSA) on Jiangsu and Dalian LNG receiving terminals. The values of impact factors are shown in Table 7.

Table 7 Impact Factors Values of Two Alternatives

	Visibility	Wind	Wave Height	Water Depth	Sediment	Potential Fatalities	Distance to populated area	VTS Coverage	SMS Level
Alternative A	22	40	4.9	50	Mixture of sand and mud	$7*10^{-5}$	3500	98%	3
Alternative B	30	30	3.1	44	Mud	$1.5*10^{-5}$	2000	90%	4

To get the expected value of each attribute for both alternatives, the utility value for the bottom hierarchy should be calculated first. Take Ua(Collision) as an example, the value of that should be calculated by sub-factors visibility, wind and wave height. Based on expert judgment records, the utility curve for visibility can be shown on Figure 2.

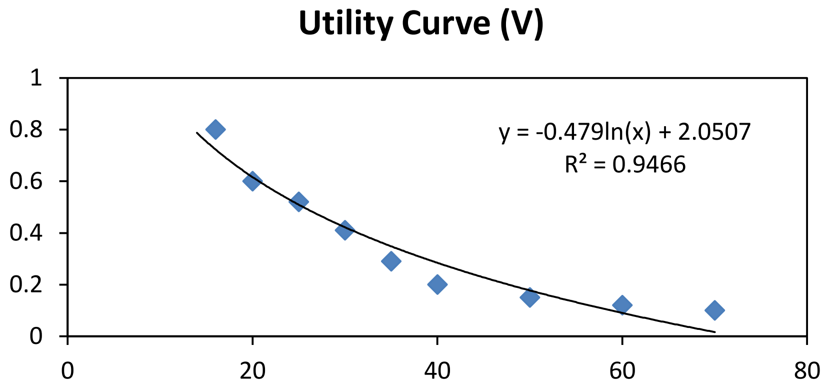

Figure 2 Utility Curve for "Visibility"

From the Figure 2, the x axis is the number of days under poor visibility per year and the y axis is the utility value of Visibility (V). Therefore,

$$\mathrm{Ua(V)} = -0.479 * \mathrm{In}(22) + 2.0507 = 0.5701$$

By applying same methodology, the utility values of "Wind" and "Wave Height" can be calculated as Ua(W) = 0.67 and Ua(WH) =0.29.

Suppose the weight vector of visibility (V), wind (W) and wave height (WH) is $(0.45, 0.35, 0.2)$, thus

$$\mathrm{Ua(Collision)} = \mathrm{k1} * \mathrm{Ua(V)} + \mathrm{k2} * \mathrm{Ua(W)} + \mathrm{k3} * \mathrm{Ua(WH)} = 0.45 * 0.5701 + 0.35 * 0.67 + 0.2 * 0.29 = 0.5490$$

The weights for water depth (WD) and sediment (S) are 0.75 and 0.25, respectively. Therefore,

$$\mathrm{Ua(Stranding)} = \mathrm{k1} * \mathrm{Ua(WD)} + \mathrm{k2} * \mathrm{Ua(S)} = 0.75 * 0.42 + 0.25 * 0.8 = 0.515$$

$$\mathrm{Ua(Navigation\ Safety)} = \mathrm{k1Ua(Collision)} + \mathrm{k2Ua(Stranding)} = 0.7112 * 0.5490 + 0.2888 * 0.515 = 0.5392$$

In the same way,

$$\mathrm{Ua(Operation\ Safety)} = \mathrm{k1} * \mathrm{Ua(Cryogenic\ Spill)} + \mathrm{k2} * \mathrm{Ua(Fire/Explosion)} = 0.2819 * 0.47 + 0.7181 * 0.65 = 0.5993$$

$$\mathrm{Ua(Management\ Level)} = \mathrm{k1} * \mathrm{Ua(VTS\ Level)} + \mathrm{k2} * \mathrm{Ua(SMS\ Level)} = 0.8500$$

By calculation, the values of Ub(Navigation Safety), Ub(Operation Safety) and Ub(Management Level) can be determined as well, as shown in Table 8.

Table 8 Utility Values of Each Attribute for Two Alternatives

Alternatives	Navigation Safety Index	Operation Safety Index	Management Level Index
A	0.5392	0.5993	0.8500
B	0.5456	0.4651	0.8100

Therefore, the total utility value for Alternative A and Alternative B can be calculated as follows.

$$\begin{aligned}\mathrm{U(A)} &= \mathrm{K1} * \mathrm{Ua(Navigation\ Safety)} + \mathrm{K2} * \mathrm{Ua(Operation\ Safety)} + \mathrm{K3} * \mathrm{Ua(Management\ Level)} \\ &= 0.5146 * 0.5392 + 0.3628 * 0.5993 + 0.1226 * 0.8500 = 0.5777\end{aligned}$$

$$\begin{aligned}\mathrm{U(B)} &= \mathrm{K1} * \mathrm{Ua(Navigation\ Safety)} + \mathrm{K2} * \mathrm{Ua(Operation\ Safety)} + \mathrm{K3} * \mathrm{Ua(Management\ Level)} \\ &= 0.5146 * 0.5456 + 0.3628 * 0.4651 + 0.1226 * 0.8100 = 0.5488\end{aligned}$$

Conclusion

Having considered three attributes, navigation safety index, operation safety index, and management level index, this paper divided each attribute into several factors. Factors were split into some sub-factors so that the values those of sub-factors can be obtained directly from previous data. Based on the outputs of the MADA model, the conclusion can be drawn in an intuitive way. Alternative A is the ideal one for the LNG-FSRU system since its total expected utility is the larger than that of Alternative B. In addition, for the first hierarchy of MADA mode, the navigation safety index and the operation safety index occupy the highest proportion of total weight.

To determine whether one location is safe to build LNG-FSRU, many more attributes should be taken into account such as extreme weather conditions, local regulations, and human factors. Beyond these factors, adequate data in different scenarios may be helpful in order to conduct a simulation closer to reality.

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