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RESEARCH ARTICLE

# Predicting Human Reliability for Shore-based LNG Bunkering Operation Process on Tanker Ships Using SLIM and Improved Z-numbers

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**Abstract**
With the increasing utilization of liquefied natural gas (LNG) as a marine fuel, the safety and reliability of shore-based LNG bunkering operations have become vital concerns. Human factors are crucial to the successful execution of these operations. However, predicting human reliability in such complex scenarios remains challenging. This paper focuses on the prediction of human reliability analysis (HRA) for shore-based LNG bunkering operations on tanker ships to address the aforementioned gap. Practical approaches to predicting HRA under the success likelihood index method (SLIM) and an improved Z-numbers approach are both adopted in this paper. SLIM provides a powerful tool to calculate human error, while the improved Z-numbers can address uncertainty and improve the reliability of qualitative expert judgments. Results show that the reliability of shore-based LNG bunkering operations is 0.861. In addition to its robust theoretical contribution, this research provides substantial practical contributions to LNG ship owners, ship superintendents, safety inspectors, and shore-based and ship crew for enhancing safety at the operational level and efficiency of shore-based LNG bunkering operations.

**Keywords** LNG bunkering operation; Success likelihood index method; Improved Z-numbers; Human reliability

## 1 Introduction

In the constantly changing environment of maritime transport, global pressure for clean and highly sustainable energy sources has led to a substantial increase in the use of liquefied natural gas (LNG) as a marine fuel. With the attempt of the shipping industry to reduce its environmental impact, adopting LNG as a bunker fuel has gained momentum, particularly in the context of tanker vessels responsible for transporting goods across vast areas of oceans worldwide. LNG is becoming an increasingly crucial component in maritime transportation due to its excellent attributes, which include low emission levels and the capacity to diminish air pollutants such as nitrogen oxide ($NO_x$) and sulfur oxide ($SO_x$). Owing to its economic and environmental advantages, LNG is also gaining widespread acceptance, particularly in the maritime sector, where it is recognized for its quality and efficient, clean energy features; thus, the demand for this resource is continuously increasing (Ahn et al., 2022; Zhu et al., 2022). The applications of LNG cover various sectors, including power generation, industrial processes, and transport. However, the transition to environmentally sustainable energy sources lies in the development and increased utilization of LNG infrastructure (Jiao et al., 2021).

The International Maritime Organization (IMO) has introduced a series of mandatory measures for ships to address the containment of greenhouse gas emissions and mitigate the environmental impact of maritime transportation (IMO, 2019; Park and Park, 2019). Consistent with the IMO directives, the objective is to achieve a minimum 50% reduction in greenhouse gas emissions from maritime transport by 2050, relative to the levels recorded in 2008 (Duong et al., 2023; Uflaz et al., 2022). These targets have considerably influenced the inclination of the maritime

**Article Highlights**

- Determining human reliability for shore-based LNG bunkering operation process for tanker vessels.
- Improved Z-number copes with the vagueness and subjectivity in the decision-making process, while SLIM systematically predicts HEP.
- Enhancing operational safety and performance reliability for shore-based LNG bunkering operation process on tankers.

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industry toward environmentally friendly alternative fuels.

Critical elements, including safety, risk factors, infrastructure, and operational protocols, are included in the LNG bunkering procedure on tanker vessels. Jeong et al. (2018) provided an overview of the current LNG bunkering methods, highlighting the practical aspects that must be considered in the research methods. Truck-to-ship, ship-to-ship (STS), and pipeline-to-ship approaches are current methodologies for LNG bunkering (Jeong et al., 2018). The emphasis on safety and risk assessment, which involve meticulous considerations such as safety exclusion zones, risk appraisal, and the design of safety zone layouts, is crucial to mitigate potential hazards effectively (Park et al., 2020; Jeong et al., 2017, 2020). Another study utilized a combination of the risk matrix approach and fuzzy evidential reasoning method to develop the hazards of LNG carrier operations and their root causes. The study found that "very high risk" hazards of LNG carrier operations (i. e., spill from transfer arm and containment system failure) pose high threats to the proper functioning of LNG carrier systems and subsystems (Nwaoha et al., 2013). Vairo et al. (2021) emphasized the requirement for dynamic risk assessment frameworks for LNG bunkering operations, revealing the importance of comprehensive and progressive research methods. Xie et al. (2022) introduced an integrated quantitative risk assessment (QRA) model to analyze the risk of fuel leakage during the locking of an LNG-fueled ship and performed a comprehensive risk analysis. Computational fluid dynamics simulations are crucial in the evaluation of safety zones and factors influencing safety, particularly in STS LNG bunkering scenarios (Vairo et al., 2021; Park et al., 2018). Furthermore, LNG bunkering stations on vessels powered by LNG necessitate the establishment of safety exclusion zones (Gucma and Gucma, 2019). Infrastructure is pivotal in the LNG bunkering domain, requiring the optimization of LNG terminal parameters to accommodate diverse gas tanker dimensions. Estimating the requisite size of LNG infrastructure is also crucial, aligning with the demand for bunkering services (Oh et al., 2020; Park and Park, 2019). Sundaram (2023) discussed the existing literature on LNG bunkering, focusing on protocols, standards, and safety, providing a foundational understanding of the current research state in the field. The expansion of LNG bunkering infrastructure is key to facilitating the provision of LNG to vessels equipped with LNG propulsion systems, ensuring seamless operational efficiency (Coimbatore and Karimi, 2023). Considerations of sustainability and environmental implications, which involve analyses such as sustainability assessments, evaluations of greenhouse gas emissions, and strategies for decarbonizing the maritime sector through the adoption of biofuels with low carbon intensity, are included in the discussion on LNG bunkering (Mandegari et al., 2023; Shao et al., 2019). In assessing human reliability in the shore-based LNG bunkering operation process on tanker ships, elucidating diverse factors influencing human error probabilities (HEPs) within such operations is imperative (Akyuz and Celik, 2015). Akyuz and Celik (2015) presented a methodological expansion to human reliability analysis (HRA), explicitly addressing cargo tank cleaning operations aboard chemical tanker ships. The shared operational environment and the necessity for dependable human performance in both contexts prove the feasibility of this approach. Additionally, Fan et al. (2022) highlighted the importance of HEP assessment for LNG bunkering, emphasizing the integral inclusion of HEPs within quantitative risk assessments for LNG bunkering operations. Furthermore, Wu et al. (2017) promoted an evidential reasoning-based approach to HRA in maritime accident processes. Their emphasis on considering distinct stages of human reliability in maritime operations offers applicability to LNG loading processes. Furthermore, Jeong et al. (2020) provided a safety assessment concerning LNG bunkering, emphasizing the importance of combining quantitative risk assessment methodologies and computational fluid dynamics simulations. This combined approach is instrumental in delineating appropriate safety zones for LNG bunkering systems, thereby ensuring the reliability of human actions in such operations (Jeong et al., 2020). Similarly, Stokes et al. (2013) evaluated competency gaps between crew members, terminal personnel, and port staff. This evaluation is crucial for mitigating risks associated with the human element in LNG bunkering, contributing to a nuanced understanding and enhancement of human reliability within shore-based LNG bunkering operations (Stokes et al., 2018). Wang and Notteboom (2015) conducted a multiple case study approach to examine the efficacy of port authorities in executing LNG bunkering projects, highlighting the advantage of empirical research methods in elucidating practical, real-world implementation. Zhao et al. (2021) introduced a comprehensive evaluation methodology for selecting sites for LNG bunkering stations, demonstrating the application of advanced analytical methods within the research framework. Chae et al. (2021) employed meta-analysis and artificial intelligence techniques for demand forecasting in LNG bunkering, revealing the potential integration of sophisticated data analysis methodologies in research endeavors. Alvarez et al. (2020) investigated the strategic and operational decision-making in expanding supply chains for LNG as a fuel, highlighting the necessity of a comprehensive research approach that addresses strategic and operational facets.

Detailed coordination of human actions, technological systems, and procedural compliance is involved in the bunkering procedure, which encompasses the transfer of LNG from shore to tanker ships. The human component within this intricate framework is crucial, substantially influencing the efficacy, safety, and overall dependability of the bunkering operation. The success likelihood index method (SLIM) is a systematic technique used to predict, evaluate, and analyze the likelihood of human error. Therefore, this method has been applied in different sectors and operations where human error is effective (Zhou et al., 2022; Liu et al., 2022). This study also used the SLIM method to evaluate the human factor during the shore-based LNG bunkering operation.

Forecasting human reliability within the scope of shore-based LNG bunkering activities on tanker ships is critically examined in this paper. The fundamental factors affecting human performance are investigated, and methodologies to strengthen predictability while mitigating potential risks are introduced. In the context of an industry transitioning toward environmentally sustainable energy solutions, a thorough understanding of the intricate challenges posed by human factors is required for the proficient execution of LNG bunkering operations. Inspection of the complex interconnections among human operators, advanced technologies, and operational procedures aims to unravel the complexities of human reliability prediction in the shore-based LNG bunkering process. This exploration aims to provide valuable insights for maritime stakeholders, contributing to cultivating a safe, efficient, and sustainable future for LNG bunkering operations on tanker ships.

## 2 Research methodology

### 2.1 Z-number theory

Zadeh (2011) introduced the Z-number theory, which constitutes an extended iteration of fuzzy set theory designed to address reliability and uncertainty simultaneously and can calculate unreliable numbers (Yousefi et al., 2021). Incomplete information is depicted within the framework of the Z-number theory, enabling the representation of fuzzy numbers as pairs where partial information is inherently processed (Alam et al., 2023). This theoretical framework contributes to heightened decision information reliability during decision-making, yielding highly rational outcomes.

A typical Z-number is of the form $Z = \left(\tilde{A}, \tilde{B}\right)$. This number is expressed as a pair, in which $\tilde{A}$ is a fuzzy set (the first component) and is represented as $\tilde{A} = \left\{x, \mu_{\tilde{A}}(x) \middle| x \in [0, 1]\right\}$, while $\tilde{B}$ describes the degree of certainty or the reliability of A (the second component) and is represented as $\tilde{B} = \left\{x, \mu_{\tilde{B}}(x) \middle| x \in [0, 1]\right\}$, where $\mu_{\tilde{A}}$ and $\mu_{\tilde{B}}$ are membership functions of $\tilde{A}$ and $\tilde{B}$, respectively (Zadeh, 2011). Uncertainties and data deficiencies are overcome by incorporating the fuzzy approach into the methodology, with expert opinions being pivotal in this context.

### 2.2 SLIM

The SLIM represents the initial iteration of HRA techniques introduced by Embrey et al. (1984). This method mainly aims to quantify and predict HEPs in specific tasks, focusing on influential factors called performance shaping factors (PSFs), which substantially impact human performance (Islam et al., 2016). The SLIM predominantly relies on the judgments of domain experts for HEP prediction due to data scarcity (Park and Lee, 2008). Drawing upon their experience and knowledge, a subset of PSFs is selected by experts, and weights are assigned to indicate their perceived importance in a given task. The systematic and careful selection of PSFs is paramount in the SLIM methodology. The core of SLIM lies in expert selection. Combined with the quantification of PSFs, a success likelihood index (SLI) is derived from expert judgments (Akyuz, 2016). Human error data can be used for SLI calibration to predict the probability of occurrence. The SLIM approach encompasses the following steps for HEP calculation (Embrey et al., 1984): PSF derivation, PSF rating, PSF weighting, SLI determination, and SLI to HEP conversion.

### 2.3 Integration of methods

Considering the case of shore-based LNG bunkering operations in maritime transportation, this section proposes a hybrid approach combining Z-numbers and SLIM to perform quantitative human error estimation. Figure 1 depicts the conceptual framework of the integration. The main steps of the proposed approach are expressed as follows.

**Step 1. Task analysis:** The first step of the proposed method involves task analysis. The relevant steps are determined in this section based on the scenario. This step deals with the activities related to the successful individual completion of the ship crew during the operation. Task analysis is performed using hierarchical task analysis (HTA), where the main task comprises subtasks (Shepherd, 2003). Therefore, HTA is performed to obtain HEP for each task.

**Step 2. Scenario definition:** The operation environment is defined in this section. This scenario may include several conditions, such as weather conditions, time of day, sea state, fatigue, workforce morale, stress, work environment, operational interruptions, noise level, and experience. Conditions are essential and must be considered because they substantially affect human performance during the performance of every task.

**Step 3. PSF derivation:** PSFs such as experience, knowledge, education, workload, fatigue, stress, task complexity, communication, and a poor working environment substantially affect human performance. The group of experts in this section elicits a set of PSFs that influence human performance during the task.

**Step 4. PSF rating:** Experts assign each value from 1 to 9 on a linear scale after PSF derivation. If a factor substan-

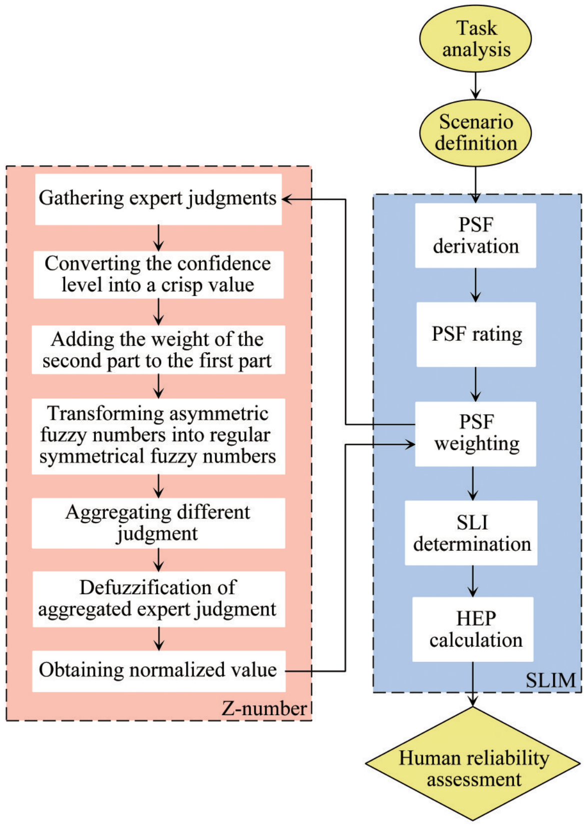


**Figure 1** Conceptual framework of SLIM in the context of improved Z-numbers

tially impacts crew performance for the relevant task, then maritime experts assign this factor a value of 1. Assessments by experts are adjusted based on conditions that arise during the task. Evaluations made by experts are independent of the influence of other PSFs.

**Step 5. PSF weighting:** Each PSF contributes relative to the others in driving human error. Accordingly, the nominated values for each PSF will vary from one expert to another. Experts weigh PSFs subjectively in traditional SLIM. Subjectivity and uncertainty in expert evaluations are addressed by weighing the PSFs using an improved Z-number, which converts the PSF weights of maritime experts into linguistic variables rather than percentage values. In this context, experts use the linguistic terms outlined in Table 1 (the initial segment of the Z-number) to demonstrate the relative importance of the PSFs of the relevant process. Subsequently, the reliability levels in Table 2 are used as a reference to ascertain the degree of certainty (the latter part of the Z-number). The evaluations provided by the experts are then translated into trapezoidal fuzzy numbers, aligning with the specifications in Tables 1 and 2.

Thus, Z-numbers containing two fuzzy sets $Z = \left[\left(a_1, a_2, a_3, a_4\right)\right], \left(b_1, b_2, b_3, b_4\right)$ are obtained from each expert (Jiskani et al., 2022). Subsequently, Kang et al. (2012) executed

**Table 1** Linguistic terms for the restrictions component of the Z-number

| Linguistic term | Trapezoidal fuzzy numbers |
|---|---|
| Very low (VL) | (0, 0, 0.1, 0.2) |
| Low (L) | (0.1, 0.2, 0.2, 0.3) |
| Slightly low (SL) | (0.2, 0.3, 0.4, 0.5) |
| Medium (M) | (0.4, 0.5, 0.5, 0.6) |
| Slightly high (SH) | (0.5, 0.6, 0.7, 0.8) |
| High (H) | (0.7, 0.8, 0.8, 0.9) |
| Very high (VH) | (0.8, 0.9, 1, 1) |

**Table 2** Linguistic terms for the reliability component of the Z-number

| Linguistic term | Trapezoidal fuzzy numbers |
|---|---|
| 0% sure | (0, 0, 0.025, 0.05) |
| 5% sure | (0.025, 0.05, 0.075, 0.1) |
| 10% sure | (0.075, 0.1, 0.125, 0.15) |
| 15% sure | (0.125, 0.15, 0.175, 0.2) |
| 20% sure | (0.175, 0.2, 0.225, 0.25) |
| 25% sure | (0.225, 0.25, 0.275, 0.3) |
| 30% sure | (0.275, 0.3, 0.325, 0.35) |
| 35% sure | (0.325, 0.35, 0.375, 0.4) |
| 40% sure | (0.375, 0.4, 0.425, 0.45) |
| 45% sure | (0.425, 0.45, 0.475, 0.5) |
| 50% sure | (0.475, 0.5, 0.525, 0.55) |
| 55% sure | (0.525, 0.55, 0.575, 0.6) |
| 60% sure | (0.575, 0.6, 0.625, 0.65) |
| 65% sure | (0.625, 0.65, 0.675, 0.7) |
| 70% sure | (0.675, 0.7, 0.725, 0.75) |
| 75% sure | (0.725, 0.75, 0.775, 0.8) |
| 80% sure | (0.775, 0.8, 0.825, 0.85) |
| 85% sure | (0.825, 0.85, 0.875, 0.9) |
| 90% sure | (0.875, 0.9, 0.925, 0.95) |
| 95% sure | (0.925, 0.95, 0.975, 1) |
| 100% sure | (0.975, 1, 1, 1) |

the transformation from Z-numbers to fuzzy numbers, which involves a three-stage process.

In the initial stage, the confidence level, which represents the second component of the Z-numbers, is converted into a crisp value using Equation (1). During this phase, definitive values are derived from trapezoidal fuzzy numbers as

$$a = \frac{\int x\mu_{\tilde{B}}(x)\,\mathrm{d}x}{\int \mu_{\tilde{B}}\mathrm{d}x} \tag{1}$$

In the second stage, the initial element of the Z-number (restriction) is assigned a weight based on the second element (reliability), incorporating the weight of the confidence level into expert opinions. The resultant weighted Z-number, which is denoted as $\tilde{Z}^{\alpha}$, is expressed as per Equation (2).

$$\tilde{Z}^{\alpha} = \left\{ x, \mu_{\tilde{A}^{\alpha}}(x) \middle| \mu_{\tilde{A}^{\alpha}}(x) = \alpha\mu_{\tilde{A}}, x \in [0, 1] \right\} \tag{2}$$

The conversion of asymmetric fuzzy numbers into symmetric fuzzy numbers is conducted during the final phase. Consequently, $\tilde{Z}^{\alpha}$ is transformed into a symmetrical fuzzy number ($\tilde{Z}'$), as delineated in Equation (3).

$$\tilde{Z}' = \left\{ x, \mu_{\tilde{Z}'}(x) \middle| \mu_{\tilde{Z}'}(x) = \mu_{\tilde{A}}\left( \frac{x}{\sqrt{\alpha}} \right), x \in [0, 1] \right\} \tag{3}$$

Individual experts provided various fuzzy reliability assessments for each event. Equation (4) consolidates these diverse evaluations, yielding a unified trapezoidal fuzzy number.

$$\tilde{A}_i^* = (a, b, c, d) = \sum_{j=1}^{8} w_j \times \tilde{A}_{ij}(a, b, c, d) \tag{4}$$

where the variable $\tilde{A}_{ij}$ represents the opinion of the $j$th expert on the $i$th PSF. $w_j$ is the weight of the $j$th expert, and the fuzzy set associated with the $i$th event is denoted by $\tilde{A}_i^*$. $\tilde{A}_i^*$ is in fuzzy form, and Equation (1) is applied for *i*ts clarification.

**Step 6. Determination of SLI:** The SLI value is obtained using Equation (5) after calculating the rating and weighting of PSFs. SLI is an essential tool for predicting the probability of events where numerous human errors may occur.

$$\text{SLI} = \sum_{i=1}^{n} r_i w_i, 0 \leqslant \text{SLI} \leqslant 1 \tag{5}$$

where $n$ represents the number of PSFs, $r_i$ denotes the rating scale of PSFs, and $w_i$ represents the weight of the relative importance of PSFs.

**Step 7. HEP calculation:** Once the SLI value is obtained, HEP values can be calculated for each task determined in the operation. SLI values can then be converted to HEP values using Equation (6), where a and b are constants obtained from the HEPs for the subtasks with the highest and lowest SLIs, respectively (Embrey et al., 1984).

$$\log(\text{HEP}) = a\text{SLI} + b \tag{6}$$

A logarithmic relationship realizes the conversion of SLI values to HEP. The main feature of the SLIM process is the log10-based linear logarithmic function given in Equation (6) (Chien et al., 1988).

## 3 Human reliability for shore-based LNG bunkering operation process on tanker ships

A shore-based LNG bunkering operation is evaluated when applying the proposed method. This operation may pose remarkable potential risks to the lives of the ship's crew, port facilities, and the marine environment. The SLIM approach is one of the excellent empirical techniques used to measure human error in shipping due to the lack of sufficient data. Similarly, a preferred application to overcome uncertainty and ambiguity in the human error detection problem is the Z-number-based fuzzy approach. The combination of the two approaches creates a unique contribution by accurately predicting the likelihood of human error for critical shipboard procedures.

### 3.1 Shore-based LNG bunkering operation onboard tanker ships

For numerous years, the propulsion systems of LNG carriers have depended on utilizing the naturally occurring boil-off of LNG stored in their cargo tanks. A fraction of LNG transitions into the gaseous phase during its discharge and storage, commonly known as boil-off gas, which can be effectively employed as a fuel source (Xavier Martínez De Osés, 2017; Dimopoulos and Frangopoulos, 2008). However, the integration of novel systems and equipment dedicated to the combustion, management, and storage of LNG is required in the incorporation of LNG as a fuel for various vessel types.

As stipulated by crews and management companies, effective countermeasures and operational protocols for LNG are crucial elements (UKP&I, 2019). LNG, which is characterized by its cold, odorless, nontoxic, and noncorrosive nature, possesses a low flashpoint and exhibits a lower density than water under atmospheric pressure conditions. Comprising predominantly methane, often exceeding 80%, with additional ethane compounds, LNG boasts the highest energy output among hydrocarbons (Yun et al., 2015). Methane vapor liquefies at temperatures below −82 ℃ and is stored at nearly atmospheric pressure, maintaining temperatures of approximately −162 ℃ (Augusto et al., 2015). Notably, gases such as LNG are environmentally cleaner compared to alternative fuels, emitting lower rates of air pollutants such as $SO_2$ and PM when subjected to combustion (IMO, 2017). The International Code of Safety for Ships Operating using Gases or Other Low-flashpoint Fuels (IGF Code), which was enacted by the IMO on January 1, 2017, establishes specific targets and standards governing the design, construction, and operation of ships utilizing such fuels (IMO, 2017). Ships intending to refuel with LNG within the purview of the IGF Code must meet designated design and feature criteria, while their operators are required to fulfill prescribed training and qualification requirements. Four LNG bunker supply options are currently available for LNG-fueled ships, leveraging current technology and equipment (UKP&I, 2019): 1) STS LNG bunkering, 2) truck-to-ship LNG bunkering, 3) terminal-to-ship LNG bunkering, and 4) utilizing containerized (portable) LNG tanks as fuel storage.

Shore-based LNG bunkering operations onboard tanker ships, in combination with stringent regulations, demonstrate a pivotal initiative in the pursuit of sustainable and environmentally conscious fueling practices in the maritime industry. This approach involves the transfer of LNG from onshore facilities to tanker ships, providing a clean and highly efficient alternative to conventional marine fuels (EMSA, 2018). The integration of regulatory frameworks ensures the adherence of the bunkering process to established standards, emphasizing safety, environmental responsibility, and operational reliability. Shore-based LNG bunkering operations, reinforced by comprehensive regulations, illustrate a harmonized approach toward fostering sustainability in maritime transportation (Peng et al., 2021). This practice not only reduces the environmental impact of shipping by integrating safety, environmental, and operational standards but also contributes to the establishment of a robust and responsible LNG bunkering infrastructure worldwide (EMSA, 2018).

Despite its minimal implementation in LNG bunkering practices, policymakers and LNG-consuming companies have developed operational checklists to address the diverse hazards and risks of LNG usage. The Advisory Committee on LNG-Fuelled Vessels, which was established in 2014 under the World Ports Climate Initiative of the International Association of Ports and Harbors (IAPH), has issued bunker checklists and guidelines for the safe execution of LNG bunkering procedures. Despite these measures, the potential for catastrophic outcomes remains, particularly given the crucial role of human factors in the bunkering process. In this context, the analysis of human reliability is necessary to ensure the safety and reliability of the shore-to-ship LNG bunkering process.

## 3.2 Problem statement

When performing a shore-based LNG bunkering operation, all relevant personnel should be familiar with the structural and technical characteristics of the ship and the operation stages that may vary depending on the conditions. Bunkering operation is an activity that has led to numerous accidents in the past due to human errors, such as incorrect adjustment of valves, inadequate tank monitoring, failure of valves, workload, fatigue, poor communication, and lack of familiarization (UKP&I, 2018). Owing to the incorrect planning of operations, precautions are not taken, risk control procedures are not implemented, and some undesirable accidents (overflow, leakage, and sea pollution) occur. Compared to traditional fuel operations, using LNG as a bunker is a new process with relatively limited experience and has operational-specific requirements. Similar to traditional bunkering operations, LNG bunkering is a crucial operation that should be conducted properly due to the dangers involved (Uflaz et al., 2022). Masters, chief engineers, officers, crew members, and other employees participating in the operation are required to receive training based on the requirements of the STCW regarding their training and qualifications. However, human errors in this new and rapidly gaining operation can be prevented by performing highly comprehensive studies. These studies should contribute to creating a risk profile for the safety of operations, calculating human errors, and determining risks and accident probability. The probability of human error is calculated in this paper, helping to increase the safety level of shore-based LNG bunkering operations.

## 3.3 Predicting human reliability

First, HTA for operation is conducted in accordance with industry bunkering guides and checklists published by organizations such as The Society of International Gas Tanker and Terminal Operators (SIGTTO), The Society for Gas as a Marine Fuel, P&I Club circulars, and expert opinions. Table 3 lists the HTA of the shore-based LNG bunkering operation. Accordingly, the operation comprises three main tasks: the planning stage, pretransfer, and after LNG transfer. Twenty subtasks are available. The tanker ship performed a shore-based LNG bunkering operation at the port of arrival, according to the scenario. The weather was partly cloudy, and the sea state was calm during the operation. The wind speed was around 10–12 kn. The ship's crew comprised two different nationalities and had adequate rest before the operation. The bunkering operation started in the morning. Participants in the operation included the chief officer, chief engineer, third engineer, bosun, pumpman, and two able seamen.

Nine experts participated in the study, and expert judgments were used for HRA. Academicians, chief engineers, and second engineers are considered maritime experts. These experts are knowledgeable, experienced, and familiar individuals in shore-based LNG bunkering operations, holding equal weighting degrees. Table 4 illustrates the details of marine experts.

First, the comments of experts were employed for the nomination of PSFs. Eight PSFs were used for the operation considered, and eight PSFs were then obtained from the literature (Akyuz, 2016). These PSFs were submitted to experts for review and received their approval. Table 5 provides the derived PSFs. Experts rate the effects of each PSF obtained for every subtask from 1 to 9. Table 6 presents the PSF ratings of all subtasks evaluated by maritime experts. The geometric mean of each PSF is computed because nine experts perform the rating process.

**Table 3** HTA of the shore-based LNG bunkering operation

| | | |
|---|---|---|
| Planning stage | 1.1 | Provide appropriate training to all personnel involved in the LNG bunker operation and increase their familiarity with specific LNG bunker equipment and procedures. |
| | 1.2 | Ensure that all LNG transfer and gas detection equipment is certified, in good condition, and suitable for the intended service. |
| | 1.3 | Ensure that the ship and the LNG bunker station agree on procedures for bunkering, cooling, and cleaning operations. |
| | 1.4 | Decide and identify restricted areas. |
| | 1.5 | Ensure that the vessel is securely moored. Comply with regulations on mooring arrangements. Provide adequate fenders. |
| | 1.6 | Position all fire extinguishing equipment correctly and make it ready for immediate use. |
| Pretransfer | 2.1 | Check that the current weather and wave conditions are within the agreed limits. |
| | 2.2 | Establish and test an effective means of communication between the responsible persons on the vessel and the LNG bunker station. Agree on the language of communication. |
| | 2.3 | Emergency stop signaling and shutdown procedures are approved, tested, and explained to all relevant personnel. Ensure that emergency procedures, plans, and contact details are known to responsible persons. |
| | 2.4 | Close external doors, portholes, and accommodation ventilation inlets according to the LNG bunker management plan. |
| | 2.5 | Operationally test the gas detection equipment and ensure that it is in good working order. |
| | 2.6 | Ensure that suitable and adequate protective clothing and equipment are immediately available for use. |
| | 2.7 | Confirm that the bunker system gauges, high-level alarms, and high-pressure alarms are operational, correctly set, and in good working order. |
| | 2.8 | Check that the Emergency Shutdown (ESD), automatic valves, or similar devices on the vessel and the LNG bunker station have been tested, have been found to be in good working order, and are ready for immediate use. |
| | 2.9 | Check the LNG bunker line and ensure that unused connections are closed, drained, and fully bolted. |
| | 2.10 | Confirm that LNG bunker hoses, fixed pipelines, and manifolds are in good condition, properly rigged, supported, properly connected, leak tested, and certified for the LNG transfer. |
| | 2.11 | Check that dry breakaway couplings in the LNG bunker connections are in place, have been visually inspected for functioning, and are in good working order. |
| After LNG Transfer | 3.1 | Maintain that LNG bunker hoses, fixed pipelines, and manifolds are purged and ready for disconnection. |
| | 3.2 | Ensure that remote and locally controlled valves are closed or set for hose disconnection. |
| | 3.3 | Check that the restricted area is deactivated after disconnection and appropriate signs are removed. |

**Table 4** Profile of marine experts

| Marine expert | Position | Years marine experienced | Education level | Shore service time |
|---|---|---|---|---|
| 1 | Academician | 6 | PhD. | 9 |
| 2 | Academician | 3 | PhD. | 12 |
| 3 | Chief engineer | 9 | MSc. | 5 |
| 4 | Chief engineer | 8 | BSc. | 10 |
| 5 | Chief engineer | 9 | MSc. | 13 |
| 6 | Chief engineer | 12 | MSc. | 4 |
| 7 | Second Engineer | 4 | MSc. | 6 |
| 8 | Second Engineer | 4 | BSc. | 4 |
| 9 | Second Engineer | 3 | BSc. | 2 |

In the step of PSF weighting, an improved Z-number approach is applied to increase the accuracy of the result. In this context, the weighting process is conducted based on the linguistic terms in Table 1 and Table 2. Table 7 shows the assessments of maritime experts regarding the weighting of PSFs. Equations (1)–(4) help determine the calculated crisp value for each PSF. The crisp values of PSFs are then normalized. Table 8 shows the aggregated fuzzy numbers, crisp values, and normalized weight of each PSF. By contrast, the weight calculation of PSF 1 (stress) is presented as an example in Table 9 to explain the computation process in detail.

**Table 5** Nominated PSFs for shore-based LNG bunkering operations

| No. | PSF |
|---|---|
| 1 | Stress |
| 2 | Complexity |
| 3 | Training |
| 4 | Experience |
| 5 | Time availability |
| 6 | Environmental factors |
| 7 | Communication |
| 8 | Safety culture |

**Table 6** Determined PSF ratings

| Subtasks | Stress | Complexity | Training | Experience | Time availability | Environmental factors | Communication | Safety culture |
|---|---|---|---|---|---|---|---|---|
| 1.1 | 7.07 | 5.42 | 5.33 | 5.52 | 4.31 | 5.63 | 4.39 | 5.84 |
| 1.2 | 7.32 | 6.21 | 5.60 | 5.86 | 5.04 | 6.28 | 5.76 | 5.71 |
| 1.3 | 2.47 | 2.39 | 2.64 | 3.82 | 3.89 | 4.86 | 2.47 | 2.71 |
| 1.4 | 6.95 | 7.07 | 5.24 | 5.36 | 5.10 | 6.08 | 5.42 | 5.20 |
| 1.5 | 3.87 | 3.49 | 3.73 | 3.70 | 4.28 | 3.70 | 3.30 | 3.70 |
| 1.6 | 7.09 | 6.60 | 5.98 | 5.73 | 4.98 | 6.32 | 5.70 | 5.29 |
| 2.1 | 7.41 | 6.76 | 5.69 | 6.16 | 6.95 | 5.63 | 6.16 | 6.07 |
| 2.2 | 4.01 | 4.01 | 3.30 | 4.01 | 4.98 | 6.02 | 2.22 | 3.40 |
| 2.3 | 4.37 | 3.45 | 3.84 | 4.01 | 4.53 | 5.86 | 3.61 | 3.02 |
| 2.4 | 6.71 | 5.84 | 3.30 | 4.36 | 5.12 | 3.87 | 5.55 | 3.75 |
| 2.5 | 5.14 | 3.75 | 3.22 | 3.82 | 4.26 | 5.74 | 4.31 | 3.42 |
| 2.6 | 6.73 | 5.92 | 4.52 | 5.12 | 5.70 | 2.83 | 6.31 | 4.23 |
| 2.7 | 3.12 | 3.13 | 3.25 | 3.89 | 3.47 | 4.26 | 3.26 | 3.32 |
| 2.8 | 2.79 | 2.92 | 3.30 | 4.07 | 3.42 | 4.86 | 3.47 | 2.26 |
| 2.9 | 5.56 | 5.08 | 3.79 | 4.17 | 4.37 | 5.51 | 4.74 | 4.08 |
| 2.10 | 6.17 | 4.17 | 3.94 | 3.52 | 4.30 | 4.40 | 4.63 | 3.41 |
| 2.11 | 6.19 | 4.68 | 3.85 | 3.54 | 3.93 | 5.25 | 5.07 | 3.03 |
| 3.1 | 3.68 | 3.73 | 3.49 | 3.45 | 3.67 | 4.10 | 3.82 | 3.74 |
| 3.2 | 6.43 | 5.31 | 4.42 | 4.28 | 4.80 | 5.82 | 4.60 | 4.28 |
| 3.3 | 7.43 | 7.06 | 5.37 | 5.71 | 5.08 | 6.83 | 4.92 | 3.93 |

**Table 7** Expert evaluations for weighting PSFs

| Expert | PSF1 | | PSF2 | | PSF3 | | PSF4 | | PSF5 | | PSF6 | | PSF7 | | PSF8 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Relative importance | Reliability | Relative importance | Reliability | Relative importance | Reliability | Relative importance | Reliability | Relative importance | Reliability | Relative importance | Reliability | Relative importance | Reliability | Relative importance | Reliability |
| E1 | SH | 70 | M | 75 | VH | 80 | H | 85 | M | 75 | L | 80 | H | 80 | H | 85 |
| E2 | M | 60 | SL | 70 | H | 100 | M | 80 | L | 85 | L | 85 | SH | 75 | SH | 70 |
| E3 | SH | 85 | M | 70 | VH | 70 | VH | 75 | SH | 80 | M | 75 | H | 85 | H | 85 |
| E4 | M | 80 | SL | 75 | M | 80 | SH | 80 | M | 90 | SL | 70 | M | 80 | SH | 80 |
| E5 | SH | 70 | M | 80 | H | 90 | H | 90 | M | 85 | M | 65 | SH | 70 | H | 75 |
| E6 | SH | 70 | M | 60 | VH | 85 | SH | 85 | M | 80 | M | 75 | M | 80 | H | 80 |
| E7 | M | 60 | SL | 55 | H | 90 | H | 100 | L | 90 | L | 80 | SH | 70 | SH | 70 |
| E8 | SL | 80 | SH | 70 | SH | 70 | SH | 90 | SL | 80 | SL | 75 | M | 75 | VH | 95 |
| E9 | M | 90 | M | 75 | VH | 75 | M | 80 | M | 75 | M | 80 | SL | 85 | SH | 85 |

**Table 8** PSF weights based on improved Z-number

| PSF | Aggregated fuzzy numbers | CV | Normalized value |
|---|---|---|---|
| Stress | (0.364, 0.451, 0.499, 0.586) | 0.475 | 0.114 |
| Complexity | (0.292, 0.376, 0.413, 0.497) | 0.394 | 0.095 |
| Training | (0.628, 0.719, 0.768, 0.820) | 0.732 | 0.175 |
| Experience | (0.536, 0.629, 0.670, 0.753) | 0.646 | 0.155 |
| Time availability | (0.292, 0.384, 0.404, 0.495) | 0.394 | 0.094 |
| Environmental factors | (0.222, 0.310, 0.329, 0.417) | 0.320 | 0.077 |
| Communication | (0.424, 0.513, 0.552, 0.641) | 0.532 | 0.128 |
| Safety culture | (0.565, 0.656, 0.705, 0.785) | 0.677 | 0.162 |

**Table 9** Weight calculation process of PSF 1

| Expert | Opinions of experts on the relative importance of PSF | | Opinions of experts on the degree of certainty | | Crisp value of the degree of certainty ($\alpha$) | $\sqrt{\alpha}$ | Fuzzy reliability judgments of experts |
|---|---|---|---|---|---|---|---|
| | Evaluation | Fuzzy numbers | Evaluation | Fuzzy numbers | | | |
| E1 | SH | (0.5, 0.6, 0.7, 0.8) | 70 | (0.675, 0.7, 0.725, 0.75) | 0.713 | 0.844 | (0.422, 0.506, 0.591, 0.675) |
| E2 | M | (0.4, 0.5, 0.5, 0.6) | 60 | (0.575, 0.6, 0.625, 0.65) | 0.613 | 0.783 | (0.313, 0.391, 0.391, 0.470) |
| E3 | SH | (0.5, 0.6, 0.7, 0.8) | 85 | (0.825, 0.85, 0.875, 0.9) | 0.863 | 0.929 | (0.464, 0.557, 0.650, 0.743) |
| E4 | M | (0.4, 0.5, 0.5, 0.6) | 80 | (0.775, 0.8, 0.825, 0.85) | 0.812 | 0.901 | (0.361, 0.451, 0.451, 0.541) |
| E5 | SH | (0.5, 0.6, 0.7, 0.8) | 70 | (0.675, 0.7, 0.725, 0.75) | 0.713 | 0.844 | (0.422, 0.506, 0.591, 0.675) |
| E6 | SH | (0.5, 0.6, 0.7, 0.8) | 70 | (0.675, 0.7, 0.725, 0.75) | 0.713 | 0.844 | (0.422, 0.506, 0.591, 0.675) |
| E7 | M | (0.4, 0.5, 0.5, 0.6) | 60 | (0.575, 0.6, 0.625, 0.65) | 0.613 | 0.783 | (0.313, 0.391, 0.391, 0.470) |
| E8 | SL | (0.2, 0.3, 0.4, 0.5) | 80 | (0.775, 0.8, 0.825, 0.85) | 0.812 | 0.901 | (0.180, 0.270, 0.361, 0.451) |
| E9 | M | (0.4, 0.5, 0.5, 0.6) | 90 | (0.875, 0.9, 0.925, 0.95) | 0.913 | 0.955 | (0.382, 0.478, 0.478, 0.573) |
| Aggregated opinions of experts | | | | | (0.364, 0.451, 0.499, 0.586) | | |
| Crisp value | | | | | 0.475 | | |
| Normalized value | | | | | 0.114 | | |

Note: Adding the weight of the second component to the first component and obtaining regular fuzzy numbers

SLIs are then computed for each subtask of the operation based on Equation (5). HEP values are finally obtained from SLI values according to Equation (6). Experts estimate the best- and worst-case scenarios during the operation to ascertain the constants a and b in Equation (6), respectively. Therefore, boundaries are established. Simultaneous equations are solved to determine the constants a and b by substituting these boundaries (SLI = 1, HEP = 0.95 and SLI = 9, HEP = $c$) into the SLIM calibration equation (Sezer et al., 2023; Abrishami et al., 2020). Table 10 depicts the SLI and HEP values for each subtask.

For shore-based LNG bunkering operations, Table 11 provides the notations used to calculate the overall HEP of all subtasks. Considering these notations, the dependency of subtasks in a system is assessed as either in series or in parallel. Subtasks are categorized as serial if the failure of one subtask leads to the inoperability of the system. Conversely, if the success of any individual subtask is adequate for the overall system functionality, then the subtasks are similar. Conversely, the relevant notation is utilized, considering the dependency among tasks (Sezer et al., 2024; Elidolu et al., 2023; He et al., 2008). Based on Table 3, the operation comprises three main tasks. With the consensus reached by marine experts, six subtasks must be appropriately fulfilled for the success of the first main task. Therefore, the system is serial. A low level of dependency exists among the six subtasks, and the total HEP is calculated as $7.39\times10^{-2}$. Similarly, HEP is found to be $1.39\times10^{-1}$ for the second main task because the system is serial, and the 11 subtasks have low dependencies. Moreover, the HEP for the third main task is calculated as $2.57\times10^{-2}$, which is attributed to the serial configuration of the system and the low dependency among its subtasks. All main tasks must be completed

**Table 10** Calculated SLI and HEP values for each subtask

| Subtasks | SLI | Log (HEP) | HEP |
|---|---|---|---|
| 1.1 | 5.45 | −2.79 | $1.61\times10^{-3}$ |
| 1.2 | 5.93 | −3.09 | $8.11\times10^{-4}$ |
| 1.3 | 3.06 | −1.30 | $4.99\times10^{-2}$ |
| 1.4 | 5.70 | −2.94 | $1.14\times10^{-3}$ |
| 1.5 | 3.71 | −1.71 | $1.96\times10^{-2}$ |
| 1.6 | 5.91 | −3.08 | $8.38\times10^{-4}$ |
| 2.1 | 6.29 | −3.32 | $4.83\times10^{-4}$ |
| 2.2 | 3.80 | −1.77 | $1.71\times10^{-2}$ |
| 2.3 | 3.95 | −1.86 | $1.40\times10^{-2}$ |
| 2.4 | 4.67 | −2.30 | $4.96\times10^{-3}$ |
| 2.5 | 4.05 | −1.92 | $1.21\times10^{-2}$ |
| 2.6 | 5.16 | −2.61 | $2.45\times10^{-3}$ |
| 2.7 | 3.43 | −1.54 | $2.91\times10^{-2}$ |
| 2.8 | 3.31 | −1.46 | $3.47\times10^{-2}$ |
| 2.9 | 4.53 | −2.22 | $6.07\times10^{-3}$ |
| 2.10 | 4.22 | −2.03 | $9.38\times10^{-3}$ |
| 2.11 | 4.28 | −2.06 | $8.61\times10^{-3}$ |
| 3.1 | 3.68 | −1.69 | $2.06\times10^{-2}$ |
| 3.2 | 4.85 | −2.42 | $3.80\times10^{-3}$ |
| 3.3 | 5.61 | −2.89 | $1.29\times10^{-3}$ |

flawlessly for the successful execution of the cargo bunkering operation. Considering the high dependency between these tasks, the final HEP value is computed as $1.39\times10^{-1}$. Furthermore, following the computation of the overall HEP value, reliability can be determined using the axiom $R = 1-\text{HEP}$ (Elidolu et al., 2023; Uflaz et al., 2024). Accordingly, the reliability of the shore-based LNG bunkering operation is calculated as $8.61\times10^{-1}$.

**Table 11** Notations related to rules

| System description | System subtask dependency | Notation for task HEP |
|---|---|---|
| Parallel system | High dependency | $\text{HEP}_{\text{Task}} = \text{Min}\left\{\text{HEP}_{\text{Sub}-\text{task i}}\right\}$ |
| | Low or no dependency | $\text{HEP}_{\text{Task}} = \prod\left(\text{HEP}_{\text{Sub}-\text{task i}}\right)$ |
| Serial system | High dependency | $\text{HEP}_{\text{Task}} = \text{Max}\left\{\text{HEP}_{\text{Sub}-\text{task i}}\right\}$ |
| | Low or no dependency | $\text{HEP}_{\text{Task}} = \sum\left(\text{HEP}_{\text{Sub}-\text{task i}}\right)$ |

## 3.4 Result and discussion

The application of the SLIM in conjunction with improved Z-numbers yielded valuable insights into predicting human reliability for shore-based LNG bunkering operations on tanker ships. The findings help improve safeguards and reduce risk in LNG bunkering operations. With the hybrid methodology in the paper, 20 tasks created by human reliability for the bunker operation conducted from the shore on LNG-fueled ships were examined.

The study results show that the human factor plays an active role in the planning phase of the operation. As shown in Table 10, subtask 1.3 (Ensure that the ship and the LNG bunker station agree on the procedures for bunkering, cooling, and cleaning operations) is the operation step with the highest HEP value ($4.99\times10^{-2}$). Preoperation loading procedures, line cooling processes, and line cleaning must be ensured when LNG fuel operation is considered holistically. In this context, the agreement regarding the operation process between the shore and the ship where the fuel operation will be performed is crucial to its safety. Different actions may be taken by shore and ship employees in a dangerous situation where effective communication cannot be established, and a consensus cannot be reached. The persons responsible for the agreement, as determined by the port and the ship, should fill out a common checklist and mutually agree on the course of the operation to prevent the aforementioned situation. The checklists should be clearly explained by these responsible persons to each employee who will participate in the operation, and the progress of the operation should not be interfered with from outside, except for the people who are informed. Among the operational tasks determined in the study, the subtask with the second highest HEP value ($3.47\times10^{-2}$) is 2.8 (Check that on the vessel and the LNG bunker station, the emergency shutdown (ESD), automatic valves, or similar devices have been tested, have been found to be in good working order, and are ready for immediate use). ESD and SSL (ship-to-shore link) systems, automatic valves, and automatically activated equipment reduce human factors during LNG bunker operation. ESD and SSL systems are crucial to improving safety during LNG transfer operations. These systems provide simultaneous ESD of ship and shore facilities in case of any abnormality detected by the ship or shore Safety Instrumented System. Therefore, the operation can be stopped without leakage or spillage, effectively reducing the risks associated with fires, explosions, or environmental hazards. The specified systems must also be checked by the shore and the ship before each operation (SIGTTO, 2017). Furthermore, regular maintenance of the systems (weekly, monthly, and annually) increases their efficiency and operability over time. Subtask 2.7 (Confirm that the bunker system gauges, high-level alarms, and high-pressure alarms are operational, correctly set, and in good working order) is the next crucial HEP value ($2.91\times10^{-2}$). High-level and high-pressure alarms prevent tank overflow and explosion due to pressure increases during operation. However, the failure of these systems to operate properly puts the entire operating process at risk. System problems during operation are avoided by conducting system tests, and warnings should be checked before operation. Personnel participating in the operation should also be informed regarding these warnings. Approved authorities should conduct condition control of valves and calibration of gauges, and repair and maintenance of equipment should be performed regularly according to the planned maintenance system (PMS). The fourth subtask with the highest HEP ($2.06\times10^{-2}$) value is 3.1 (Maintain that LNG bunker hoses, fixed pipelines, and manifolds are purged and ready for disconnection). Essential points to be considered in manifold disassembly after completion of the LNG bunker operation involve evacuation of the circuits before dismantling and prevention of the LNG liquid phase from encountering oxygen during disassembly. These points are especially important to prevent personnel from contacting fuel during disassembly. The personnel performing this operation on the ship must be familiar with the valve systems, and the valves must be numbered to avoid confusion. The manifold and drain valves of the ship must be closed and opened, respectively, before starting the draining process. Afterward, the line to which the arm is connected is pressurized by the land station, the LNG remaining inside the hose is purged, and the hoses are safely ready for disassembly. Another important subtask is 1.5 (Ensure that the vessel is securely moored. Comply with regulations on mooring arrangements. Provide adequate fenders), with a HEP value of $1.96\times10^{-2}$. Proper ship mooring to the shore prevents unwanted stresses in the hose or manifold area during bunker operation. If the mooring equipment and fender requirements are not met, then the heel created by any ship passing close may cause the activation of the ESD system. In addition, ropes that are not connected in sufficient numbers may create the possibility of breaking when a load is placed on them, producing unwanted tension in the manifold and activating the ESD system. The ship-specific mooring plan has been discussed with the mooring master to avoid this situation. In addition, any changes that may occur in the ropes according to weather and tide conditions should be calculated and reported to the personnel, and the condition of the ropes should be observed regularly. Rope breaking may be prevented by conducting Brake Holding Capacity tests on mooring winches, and maintenance must be conducted in accordance with PMS (MEG4, 2018).

## 4 Conclusion

The use of LNG as fuel in maritime transportation has become a prominent topic in recent years due to its high efficiency and minimal environmental concern. This situation causes a substantial increase in the transportation, storage, and use of LNG as fuel worldwide. However, LNG is a refrigerated liquid with vapor dispersion properties and becomes flammable at high temperatures, making the LNG bunkering operation risky. A possible accident during a land-to-ship LNG fuel operation may lead to consequences such as fatalities and losses of the ship and cargo. The shore-to-ship LNG bunkering operation comprises several steps, each based on the human factor, which may introduce errors at every step. In this context, this paper proposes a conceptual framework for the systematic evaluation of human reliability probability for a shore-based LNG bunkering operation process with SLIM and an improved Z-numbers approach. SLIM is a practical method to calculate human error. However, this method may face the problem of combining multiple experts, such as selecting multiple PSFs and assigning different weights to PSFs. The improved Z-numbers theory, which considers vague, imprecise, and incomplete information, is used to address this situation. The findings of the research show that the reliability of shore-based LNG bunkering operations is 8.61E-01. This result is reasonable but not at the desired level for the process. Various factors were also identified in this study as triggering human errors that should be addressed, including ineffective safety culture, experience, complexity, and limited time. Furthermore, the proposed approach can effectively be applied to identifying operational vulnerabilities and critical human errors. The findings of the paper provide remarkable contributions to LNG ship owners, ship masters, officers, ship superintendents, safety inspectors, shore-based crew, and ship crew for enhancing safety at the operational level and efficiency of shore-based LNG bunkering operations. The number of experts can be considered a limitation of the study but can be relatively extended in future research or can be overcome by providing an actual operational dataset. Future research will address data derivation and uncertainty in probabilistic reliability assessment in a simulation environment.

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