A human reliability analysis for ship to ship LNG bunkering process under D-S evidence fusion HEART approach.

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Abstract

LNG (Liquid Natural Gas) ship to ship bunkering process is quite a new concept for the maritime industry since the usage of LNG has been increasing worldwide. The LNG bunkering process poses a high risk due to human errors, while a minor error may be catastrophic. The expectation of the ship`s crew is to carry out operations without any errors. Therefore, human reliability analysis (HRA) is paramount to improving operational safety during the ship to ship LNG bunkering process. In this context, this paper performs a systematic HRA under the D–S (Dempster-Shafer) evidence fusion-based HEART (human error assessment and reduction technique) approach. While the HEART quantifies human error for the tasks being performed, the extended D-S evidence fusion deals with the limitation of APOA (assessing the proportion of effect) calculation since it significantly relies on evaluating a single rater. The finding shows that human reliability for the ship to ship LNG bunkering process is 5.98E-01 and reasonable, but not at the desired level. The paper`s outcomes will contribute to the utmost for LNG ship operators, safety inspectors, and ship owners to establish a safe and efficient ship to ship LNG bunkering process and minimise human error-based accidents.

Keywords: Human reliability, D-S evidence fusion theory, HEART, LNG bunkering process.

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1. Introduction

The world's marine transportation sector has already taken operational and technical strategies to limit greenhouse gas emissions (GHG). With MARPOL (International Convention for the Prevention of Pollution from Ships) Annex VI, which took effect on 1 January 2013, the IMO (International Maritime Organization) introduced a new strategy for reducing carbon emissions and preserving ship energy efficiency (IMO, 2017a). In this context, the Marine Environment Protection Committee (MEPC 72) of the International Maritime Organization (IMO) established a more strict emission reduction strategy for greenhouse gases (GHG) and proposed a reduction of GHG emissions from international shipping by at least 50 per cent annually by 2050 (IMO, 2018). Energy efficiency has already become a necessity in maritime transportation as a result of higher marine fuel costs, increases in taxes, and air pollution requirements. To comply with the IMO's targets, it is essential to adopt and encourage new technologies, alternative fuels, and alternative energy sources on all ships worldwide to reduce ship-related greenhouse gas emissions (Faber et al., 2019). The IMO declared to decrease the sulphur content of ships' fuel oil to 0.5 per cent (from 3.5 per cent) on January 1, 2020, in line with European regulations (IMO, 2018). This resolution will likely substantially affect ship fuel use and stimulate demand for alternative fuels. Nowadays, alternative fuels such as bio methanol (Faber et al., 2019), ammonia (Bicer and Dincer, 2018), dimethyl ether (Juan-Alcañiz et al., 2010), biodiesel (Mohd Noor et al., 2018), fuel cells (Van Biert et al., 2016) and gaseous fuels including LNG (Liquefied Natural Gas) (Burel et al., 2013) are indeed offered for maritime transportation.

On the other hand, in the process of introducing and using alternative fuels, there are many difficulties, such as determining the emissions of fuels, their prices, availability of supply, the technical suitability of ships, the structural suitability of ports, and expertise (Prussi et al., 2021). New technological systems introduce new safety concerns, and human interaction is still required (Fan et al., 2022). Human reliability, therefore, plays a crucial role in improving shipboard safety. Due to the strict enforcement of environmental restrictions, ship owners are investigating using clean alternative fuels to reduce emissions from ships while maintaining within the prescribed limit. LNG was determined to be more favourable than other alternative fuels and began to be used as a ship fuel (Prussi et al., 2021). Furthermore, the International Gas Union's 2021 report states that using LNG as a ship fuel is a feasible alternative for preventing air pollution and adhering to strict emission regulations. LNG is now the most cost-effective and readily available technology for reducing the environmental impact of maritime shipping and preserving air quality on a large scale (IGU, 2021). According to Sphera, greenhouse gas (GHG) emissions reductions of up to 23% are now possible by using LNG as a marine fuel, based on the new equipment and technology adopted (Sphera, 2021). Environmental impacts and reasonable price conditions make LNG fuel a more sustainable alternative than conventional fuels (Prussi et al., 2021). There are currently 572 LNG ships (LNG as a cargo) in operation, according to the IGU (International Gas Union) 2021 report (IGU, 2021). Transportation of LNG as cargo is widespread; therefore, both ship owners and crew members are familiar with LNG-carrying ships' operations due to regulations, specific inspections, and established safety culture. In the IGU 2021 report, it is stated that the number of LNG bunkering vessels is 22, the LNG terminals and ports are 44, and most of them are operated in Europe (IGU, 2021). At the same time, according to the 2021 DNV GL reports, it is stated that the number of ships using LNG fuel is 198. Due to the beneficial environmental consequences and benefits associated with safe processes, studies have highlighted that the number of ships utilising LNG fuel and facilities delivering LNG fuel will increase in the future (DNV, 2021; Sun et al., 2017). Considering all this, the performance of the ship crew during the ship to ship LNG bunkering process becomes a very critical issue.

1.1. Literature reviewing

LNG is a natural gas that inherently contains fire and explosion hazards, so the bunkering, storage, and transportation of LNG fuel is an operation that requires great care. In recent years, there has been an increase in literature on LNG bunkering, with most of this literature comprising risk assessment studies (Aneziris et al., 2021; Fu et al. 2016; Noh et al., 2014). For instance, Gerbec and Aneziris (2022) performed a risk assessment on uncertainties in failure rates of bunkering arms and hoses for LNG bunkering. Fan et al. (2021) conducted a risk assessment to generate a data set of dynamic risk assessments for LNG bunkering during simultaneous operation. Lee et al. (2021) investigated the optimal LNG bunkering methods for shipyard safety using the analytic hierarchy process. In the study, they concluded that the ship to ship bunkering was chosen with the highest weight among the LNG bunkering methods by experts. Iannaccone et al. (2021) conducted risk assessments for the passenger's vessels by developing possible scenarios for port operations during the LNG bunkering operation. Jeong et al. (2018) utilised a probabilistic risk assessment strategy to establish the safe exclusion zone surrounding LNG bunkering stations based on the determined LNG bunkering risk. Similarly, Park and Paik (2022) discussed the safe zone design during truck to ship bunkering.

In the literature, studies have also focused on the economic benefits and economic analysis of ships using LNG fuel (Lee et al., 2020), LNG bunkering facilities (Calderón et al., 2016; Park and Park, 2019), environmental effects of LNG fuel and reducing emissions, feasibility, and economic impact (Schinas and Butler, 2016). Various studies examined safety concerns associated with LNG operations (Animah and Shafiee , 2020; Sultana et al., 2019; Lee et al., 2015; Alderman, 2005), specifically in terms of LNG storage and bunkering facilities (Aneziris et al., 2020), safety assessment of alternative technologies used in LNG bunkering (Iannaccone et al., 2019) and resilience assessment of LNG bunkering with a decision support system (Vairo et al., 2020).

There are also some studies on human errors. Fan et al. (2022) analysed the human error probabilities for LNG bunkering operation with a quantitative method Fuzzy Bayesian CREAM model. In this study, HEPs were estimated by evaluating safety philosophical factors. Stokes et al. (2013) performed a study about the human factor in LNG bunkering operations and stated that the competencies of crew and staff are essential to enhance safety. When investigating human error and reliability in LNG bunkering operations, it has been revealed that there is insufficient research in this area.

These studies confirm the significance of the human element and demonstrate that human error has been the leading cause of accidents. There are different LNG bunkering operations, including ship-to-ship, truck-to-ship, shore-to-ship, etc. Consequently, each distinct type of operation involves its hazards and control measures. To address this gap in the literature, the purpose of this study was to evaluate the importance of human reliability in LNG ship bunkering. Ship crews perform critical tasks during the ship to ship LNG bunkering process. To successfully complete the process, it is essential to carry out the tasks without making errors. In this context, the human factor is paramount to enhancing process safety and minimising potential accidents.

According to the statistics, more than 80 per cent of maritime accidents are due to human error (Liu et al., 2021; Khan et al., 2020). Human errors' contribution to maritime and offshore industries have been widely discussed in different topics such as maintenance in petrochemical plants (Rozuhan et al., 2020), floating offshore structures (Abaei et al., 2019; Akyuz and Celik, 2016), critical shipboard operations (Erdem and Akyuz, 2021; Kandemir et al., 2019; Akyuz, 2016), and ship collision (Arici et al, 2020; Aydin et al., 2021a). Marine and offshore safety practitioners encourage additional study publications as human error-related accidents continue to occur. In addition, HRA techniques using expert judgments such as Cognitive Reliability and Error Analysis Method (CREAM) (Elidolu et al., 2022; Aydin et al., 2021b), Success Likelihood Index Method (SLIM) (Uflaz et al., 2022), Human Factors Analysis and Classification System (HFACS) (Qiao et al., 2020), HEART (Akyuz et al., 2018; Islam et al., 2017) are generally adopted in human reliability analysis studies in the maritime literature. On the other hand, techniques such as fuzzy logic (Ahn and Kurt, 2020), analytical hierarchy process (Akyuz and Celik, 2015a), evidential reasoning (Wu et al., 2017), Bayesian network (Yang et al., 2019) are integrated into the methodologies in order to analyse the studies more effortlessly and to overcome some uncertainties. The D-S evidence theory is preferred to fuse expert opinions in this paper. In this context, the different effect rates determined by the multiple experts for the same EPCs are combined with the D-S evidence theory. Thus, the problem of combining the opinions of multiple experts can be solved.

1.2. LNG Bunkering fundamentals

Even though conventional fuel bunkering has become routine, it remains a critical and dangerous job. From this point of view, LNG bunkering is a relatively new bunkering operation, and it exposes the ship to several threats due to the variety of approaches used. Consequently, both the LNG bunker and LNG-fuelled vessels should develop a strategy to ensure a safe operation. Authorised persons should conduct the necessary controls in compliance with all existing international and national regulations. Furthermore, it is essential to prevent human error by ensuring that all personnel involved in the LNG bunkering operation meet the minimum training standards. The minimum training requirements for seafarers taking part in LNG bunkering operations are essentially covered by Regulation V/3 of the STCW (International Convention on Standards of Training, Certification, and Watchkeeping for Seafarers) Code and detailed in Section A-V/3 of the STCW Code (IMO, 2015). The person in charge should be familiar with the risks of the process of LNG bunkering (Fan et al., 2021) , the operational rules (Wang and Notteboom, 2015) and systems, the requirements of the ship to ship operation, possible emergency procedures for fire and explosion (Aneziris et al., 2014; Mokhatab et al., 2013). In addition to this knowledge, the adequate rest of key personnel is crucial for preventing potential dangers, particularly with regard to human element issues (Stokes et al., 2013).

All relevant stakeholders in the LNG bunkering are expected to be familiar with the ship's operational stages during the bunkering, which may vary depending on the ship's structural and technical features and the location of the operation. Humans play a role in maritime facilities' design, operations, maintenance, and administration. As a result of this considerable involvement, human factors are commonly identified as a reason for marine accidents. In order to preserve safety, the human aspect must be considered at all stages of any type of bunkering operation. Traditional bunkering is a frequent activity on board a ship that has been the cause of multiple accidents in the past due to human errors such as the improper setting of valves, insufficient tank monitoring, malfunction of valves, complacency, high workload, fatigue, poor communication, and unfamiliarity (UKP&I, 2018). It is also critical that bunkering operations are well planned throughout and that the essential risk control procedures are in place to prevent an incident and facilitate an efficient reaction. There are still some undesirable accidents in bunkering operations today (such as overflow, leakage, sea pollution, etc.). Like conventional refuelling bunkering, LNG bunkering is a substantial threat that must be carried out properly due to its inherent dangers. The operation of LNG fuel is a recent process with limited experience; for this reason, many policy-making and supervisory organisations have developed procedures and operational checklists for shore and ship staff. Captains, chief engineers, officers, crew members, and other workers involved in the operation are expected to acquire training consistent with the STCW Code's requirements for their training and qualifications. Consequently, the studies to be conducted in this field should contribute to the formation of a risk profile, the calculation of human errors, the identification of risks and precautions, and the determination of the probability of accidents in the sector, all of which will contribute to the safety of operations.

Since the number of ships using LNG fuel and facilities providing LNG fuel has been growing gradually, analysing the human reliability of ship to ship LNG bunkering process has remained limited. Previous research has not investigated human reliability analysis (HRA) in LNG ship to ship bunkering. This research seeks to obtain human error probability (HEP), which will help address the aforementioned gaps and improve the safety level of LNG bunkering.

In the view above, although there is limited research on D-S-based HEART methodology in the maritime industry, there is a lack of research that directly deals with human error and the reliability of the ship to ship LNG bunkering process. Therefore, this paper remedies the gap by performing a systematic HRA under an extended D-S evidence fusion HEART approach to enhance safety and minimise human error in LNG-fuelled ships. In this context, the paper is organised as follows. Section 1 gives a short explanation of why the study was done, as well as a detailed review of the literature and a look at how LNG is moved by sea. Section 2 introduces methodologies. Section 3 performs HRA for the ship to ship LNG bunkering. Finally, the conclusion regarding the subject is mentioned and recommendations for future research are provided in Section 4.

2. Methodology

2.1. HEART

Human error assessment and reduction technique (HEART) was introduced to conduct an empirical human error and reliability prediction (Williams, 1988). The method provides a practical tool to estimate HEP for a specific task in the operational system. HEART is a modelling tool applied in safety and reliability analysis in many industries, such as railways (Wang et al., 2018), nuclear power plants (Kirwan et al., 2005), the business world (Evans et al., 2019a) and occupational health (Aliabadi, 2021). In cases where human error data is scarce, it is very challenging to estimate HEP by applying stochastic models such as Bayesian networks or Markov chains. Also, many of the other HRA methodologies available are limited in their ability to reveal all significant aspects of the human factor. Therefore, it is more reasonable to use a technique such as HEART that allows the evaluation of human performance as a whole. HEART is a robust and straightforward tool that evaluates human tasks to calculate the HEP value. There are two fundamental parameters to calculate HEP; generic task type (GTT) and error-producing condition (EPC) (Deacon et al., 2013; Liu and Zhang, 2020; Noroozi et al., 2014). The GTT assists users in capturing appropriate tasks under HRA and defines the generic error probability (GEP) value. The EPC defines the performance shaping factor which influences the probability of human error in the associated task. As a result, the data set covers multiple HEP values derived from different domains such as nuclear power plants, the petrochemical industry, offshore platforms, the service industry, etc. (Williams, 1988). In the method, there are nine GTTs defined and those are addressed to GEP values. After that, the EPC is determined by experts. The EPCs are significant factors such as operator experience, limited time, familiarity, fatigue, noise level, etc., which may significantly affect human performance and increase HEP. There are thirty-eight different EPCs assigned in the original HEART approach (Williams, 1988) and generally these EPCs are considered in studies (Navas et al., 2022; Aliabadi, 2021; Evans et al. 2019b).

2.2. D-S evidence fusion theory

The D-S evidence theory is a method of analysis for data representation and reasoning purposes, considering uncertain, imprecise, and incomplete information (Sentz and Ferson, 2002). The method was first presented by Dempster (Dempster, 1967) and then expanded by Shafer (Shafer, 1976). The theory is a powerful mathematical framework used today when it comes to situations such as uncertainty (Sezer et al., 2022), multi-source information fusion (Li et al., 2021; Zhu and Xiao, 2021) and decision-making with uncertain information (Liu and Zhang, 2020).

Let Θ be the universal set titled Frame of discernment (FOD). This set contains all possible states $\{H_1, H_2, \dots, H_n\}$. In addition, 2^Θ represents the power set of the versatile collection. Therefore, each element of 2^Θ has a value in the range of [0,1].

$$\Theta = \{H_1, H_2, \dots, H_n\} \tag{1}$$

$$2^\Theta = \{\emptyset, \{H_1\}, \{H_2\}, \dots \{H_n\}, \{H_1 \cup H_2\}, \dots, \{H_1 \cup H_2 \cup \dots H_i\}, \dots \{H_1 \cup H_2 \cup \dots H_n\}\} \tag{2}$$

The basic probability assignment (BPA) function refers to the amount of data obtained from different sources, and Θ has a relationship with each power set. The representation of the BPA function and the assumptions it should provide are as follows.

$$m: 2^{\Theta} \rightarrow [0,1] \tag{3}$$

$$m(\emptyset) = 0 \tag{4}$$

$$\sum_{A \in 2^{\Theta}} m(A) = 1 \tag{5}$$

The expression $\emptyset$ in equation 4 symbolises the empty set and means there is no possibility for the relevant parameter to be found outside FOD. An in Equation 5 denotes any power set of FOD and is called the focal element. The mass function m(A) shows the extent to which the evidence backs A.

D-S evidence theory demonstrates the rule of combining data from independent and various sources. According to this rule, when more than one mass function, BPA, is given from the same FOD, it can be combined. The Dempster combination rule is as follows:

$$m_{12}(A) = \begin{cases} \frac{\sum_{B \cap C \neq \emptyset} m_1(B) m_2(C)}{1-k}, A \neq \emptyset \\ \quad 0,\ A = \emptyset \end{cases} \tag{6}$$

$$k = \sum_{B \cap C = \emptyset} m_1(B) m_2(C) \tag{7}$$

m_1 and m_2 are two independent BPA functions. Thanks to Dempster's rule of combination, the total belief level of the two functions is determined. m_{12} stands for combined BPA. k is expressed as the conflict coefficient and depicts the conflict between m_1 and m_2.

The D-S evidence theory is adapted according to HEART as follows. If we assume that the number of experts making EPC evaluations is n, this can be shown as $E = \{e_i | i = 1, 2, \dots n\}$. In this study, FOD comprises thirty-eight EPCs. Assuming an expert selects one or more EPCs, the FOD can be a set like $\Theta = \{\mathrm{EPC}_t | 1, 2, \dots 38\}$. Let's think that $\mathrm{EPCs} = \{\mathrm{EPC}_l, EPC_m\}$ are the focal elements contained in FOD and procured from experts in e_q and e_p $\left(p \neq q; p, q \in (1, n)\right)$. These are pieces of evidence to which the fusing process was applied. It satisfies equation 5 $\sum_{l=1}^{38} e_p(EPC_l) = 1; \sum_{m=1}^{38} e_q(EPC_m) = 1$ (Zhou et al., 2019).

Pieces of evidence from different sources can be brought together with the help of the Dempster combination rule (Wang et al., 2021). The customisation of the combining rule in Equation 6 for HEART is as follows.

$$e_{p,q} = \begin{cases} \dfrac{\sum_{EPC_l \cap EPC_m \neq \emptyset} e_p(EPC_l)e_q(EPC_m)}{1 - k_{(\mathrm{ep,eq})}}, A \neq \emptyset \\ 0, \quad A = \emptyset \end{cases} \tag{8}$$

Where, k(e_p, e_q) is the coefficient of conflict between the evidence and expresses the extent of the disagreement between the experts and is denoted as:

$$k(e_p, e_q) = \sum_{EPC_l \cap EPC_m = \emptyset} e_p(EPC_l)e_q(EPC_m) \tag{9}$$

Zadeh observes that the Dempster combination rule leads to illogical conclusions when the evidence is highly conflicting. When k → 1, the evidence has a high conflict coefficient, which means unreasonable results can occur. Besides, in the case of k = 1, the Dempster combination rule cannot be used. A modified rule may be needed to solve these problems (Wang et al., 2021; Zadeh, 1984). This paper applies equations 10-15 to deal with the conflict coefficient problem (Zheng et al., 2017; Zhou et al., 2019).

In this context, the combining rule is applied with the help of cross-merging in the paper. First, similarity coefficients based on cosine similarity are calculated from the evidence obtained from experts (Chen and Zhang, 2021; Liang et al., 2016). e_p and e_q are two pieces of evidence, and the calculation of the similarity coefficient (sim (e_p, e_q)) between them is as follows:

$$sim(e_p, e_q) = \frac{\sum_{EPC_l \cap EPC_m \neq \emptyset} e_p(EPC_l)e_q(EPC_m)}{\sqrt{\left(\sum\left(e_p(EPC_l)\right)^2\right) . \left(\sum\left(e_q(EPC_m)\right)^2\right)}} \tag{10}$$

After determining the similarity coefficient of each pair of evidence, assuming that the number of evidence is n, the similarity matrix is created as in equation 11.

$$s = \begin{bmatrix} 0 & \mathrm{sim}_{(e_1,e_2)} & \cdots & \mathrm{sim}_{(e_1,e_n)} \\ \mathrm{sim}_{(e_2,e_1)} & 0 & \cdots & \mathrm{sim}_{(e_2,e_n)} \\ \cdots & \cdots & \cdots & \cdots \\ \mathrm{sim}_{(e_n,e_1)} & \mathrm{sim}_{(e_n,e_2)} & \cdots & 0 \end{bmatrix} \tag{11}$$

Then, the degree of support of the evidence is computed with the help of the degree of similarity. The sum of the similarity between the other evidence and the e_p indicates the degree of support of the e_p and is denoted as sup(e_p). The high level of similarity between one piece of evidence and other evidence leads to a high degree of support (Dong et al., 2011; Guo and Li, 2011). The degree of support for each piece of evidence is defined as follows.

$$\sup(e_p) = \sum_{q=1, q\neq p}^{n} sim(e_p, e_q) \quad (p = 1,2, \ldots n) \tag{12}$$

The degree of support of evidence allows us to know about the reliability of the evidence (Guo and Li 2011). The credibility (Crd) of e_p is calculated by applying the normalisation process and is provided as follows.

$$Crd(e_p) = \frac{\sup(e_p)}{\sum_{p=1}^{n} \sup(e_p)} \quad (p = 1,2, \ldots n) \tag{13}$$

The weighted average of the basic true distribution for each EPC is obtained using equation 14 after the credibility process, which expresses the relative importance of each piece of evidence, is completed. In the light of f equation 15, the weighted averages of the basic true distribution are normalised and the $\overline{APOA}$, which is the fused version of each EPC, is determined.

$$e_c(EPC_t) = \sum_{p=1}^{n} e_p(EPC_t).Crd(e_p) \quad (t = 1,2, \ldots, 38) \tag{14}$$

$$\overline{APOA}_t = e(EPC_t) = \frac{e_c(EPC_t)^2}{\sum_{t=1}^{n} e_c(EPC_t)^2} \quad (t = 1,2, \ldots, 38) \tag{15}$$

2.3. Integration of methodologies: An extended D-S evidence fusion HEART

Integration of D-S evidence theory into HEART to implement more accurate HRA in shipboard operations is delineated in the flow diagram in Figure 1.

<Figure 1> is inserted here.

According to Figure 1, firstly, task analysis is performed to detect the tasks of the process under consideration. Then the scenario is defined in order to know the process conditions. In light of all these, HEART, one of the human reliability analysis methods, is applied. Accordingly, the GTT and EPCs of each task are determined by the experts. Modified D-S evidence theory is carried out to fuse different EPC assessments from multiple experts. In this context, firstly, the similarity coefficients between the evidence derived by the experts are obtained (Eq. 10). The similarity matrix is defined by means of similarity coefficients (Eq. 11). With the help of the similarity matrix, the support degree of each expert is determined (Eq. 12). The credibility of each expert is specified by applying the normalization process to the support degree (Eq. 13). The credibility of each expert and the degree of belief in the EPC allows to obtain the basic true distribution of each EPC (Eq. 14). Finally, the basic true distributions of the EPCs are normalized to obtain the weight of each EPC, that is, the fused APOA value (Eq. 15). The original HEART method is used to find the HEP value of each task. Various notations are taken into account to determine the overall HEP value of the process. Details of the main steps of the approach are provided below.

Step 1. Task analysis: In the first step, the tasks of the activity are compiled by bringing them together. Task analysis is conducted in accordance with hierarchical task analysis (HTA), in which main tasks are separated into sub-tasks (Akyuz and Celik, 2015a; Shepherd, 2000). The tasks of the activity that must be completed successfully are considered. Thus wise, HEP values of main tasks and sub-tasks can be estimated.

Step 2. Scenario definition: In this step, instant situations are explained to account for various conditions such as physical working conditions, limitations of the operation, and the situations of the persons performing the task (Akyuz et al., 2018; Aydin et al., 2021). These conditions that affect human performance during the execution of each sub-task are quite substantial in determining GTT and EPC.

Step 3. GTT selection: This step aims to assign the most appropriate of the nine GTTs from A to M associated with each identified sub-task. The quantitative value, called GEP, of each specific task evaluated with the help of the GTT and determined by the experts, is detected (Kirwan and Gibson, 2008).

Step 4. EPC/s selection: After determining the GEP value of each sub-task, EPCs that enhance the probability of human error are included in the analysis process. The experts select the most suitable EPCs for the sub-tasks concerning the scenario. If the expert makes multiple selections among the EPCs identified for HEART, the APOA calculation is needed to assign the overall impact of the EPCs.

Step 5. APOA calculation: In the APOA calculation, the proportion of the EPC impact is determined. This paper adopts a modified D-S evidence theory instead of traditional APOA calculation. This improves the accuracy of the calculation for human reliability analysis by appointing the impact ratio of each EPC. Due to the selection of multiple EPC at this stage, multi-experts may assign different effect weights to evaluate EPCs. The problem of fusing multi-expert-based EPCs is solved in this step.

Step 6. HEP calculation: After determining the GEP, EPC, and $\overline{APOA}$ values for each sub-task, the HEP values of the sub-tasks can be calculated using the formula below (Williams, 1988).

$$\mathrm{HEP} = \mathrm{GEP} \times \left\{\prod_{t}[(EPC_t - 1)\overline{APOA}_t + 1]\right\} \tag{16}$$

According to equation 16, EPC_t is the t^{th} $(t = 1,2,3, \ldots 38)$ EPC and $\overline{APOA}_t$ is the fused $\overline{APOA}$ value of EPC_t.

Step 7. Reliability assessment: After acquiring the HEP values of the sub-tasks, some notation can be considered to calculate the total HEP of all the tasks. Table 1 contains the notations mentioned (He et al. 2008).

<Table 1> is inserted here.

According to Table 1, the tasks of a system can be connected in parallel or in series. Failure of a sub-task can cause the system to fail. In this case, it is assumed that the tasks are connected in series. If a sub-task fails and the system continues to run, it is considered that the tasks are connected in parallel (Akyuz and Celik, 2015a). On the other hand, considering the dependency status of the sub-tasks of the system, the relevant formula is used.

Furthermore, the probability of a system operating without errors or failures is called reliability, and the equation $R(t) = 1 - F(t)$ is the formulation of this definition. $R(t)$ denotes reliability while $F(t)$ denotes failure probability (Akyuz and Celik, 2015b).

3. Human reliability analysis for ship to ship LNG bunkering.

This section performs an empirical HRA for the ship to ship LNG bunkering process to enhance operational safety levels and minimise potential risks in maritime transportation.

3.1. LNG as fuel onboard ship

For decades, the engines of LNG carriers have been powered by the natural boil-off of the LNG stored in their cargo tanks. During the LNG discharge and storage process, a portion of the LNG evaporates into the gas phase, which is typically referred to as boil-off gas and can be utilised as fuel (Sastre Buades, 2017). Installing LNG as a fuel on other types of vessels, however, requires the installation of new systems and equipment for burning, handling, and storing the LNG.

LNG effective countermeasures and operating procedures on the part of crews and management companies (UKP&I, 2019). The LNG is a cold, odourless, non-toxic, non-corrosive liquid with a low flashpoint and has a lower density than water kept at atmospheric pressure. LNG has the most considerable energy output of any hydrocarbon and is composed primarily of methane (often more significant than 80%), with some ethane mixes. Methane vapour liquefies at temperatures below -82°C and is stored at near atmospheric pressure at temperatures of approximately -162°C (Alderman, 2005; UKP&I, 2019). Gas and other low-flashpoint fuels are considered cleaner than different fuel types because they emit air pollutants such as SO_2 and PM at lower rates when burned (IMO, 2017b). The International Code of Safety for Ships Operating using Gases or Other Low-flashpoint Fuels (IGF Code), which was adopted by the International Maritime Organization (IMO) on January 1, 2017, established some targets and standards for the design, construction, and operation of ships operating on this type of fuel (IMO, 2017b). Ships that will refuel LNG within the scope of the IGF Code should fulfil specific design and feature requirements, and their operators should satisfy specific training and qualification requirements. Four LNG bunker supply options are available to LNG-fuelled ships using existing technology and equipment (UKP&I 2019): i.) Ship-to-ship (STS) LNG bunkering, ii.) Truck-to-ship LNG bunkering, iii.) Terminal-to-ship LNG bunkering, iv.) Containerized (portable) LNG tanks are used as fuel tanks.

All of those bunker delivery techniques involve unique regulations and equipment, and the STS bunkering method provides for more flexible terms and the delivery of more significant amounts of LNG (Arnet, 2014; EMSA, 2018; Jeong et al., 2018). Ship-to-ship LNG bunkering operations can take place in either port areas or the open sea and provide several operational advantages.

Ship-to-ship LNG bunkering can take place alongside facilities and at anchorages within port boundaries through the fuel hose. It is not conventional to conduct LNG bunkering operations while the ships are underway and should not be performed without all the appropriate STS mooring and fendering systems (EMSA, 2018; UKP&I, 2019). Although it is not extensively used in LNG bunkering, policymakers and companies that consume LNG fuel have established operational checklists due to the various hazards and risks associated with LNG. The Advisory Committee on LNG-Fuelled Vessels, organised in 2014 as part of The International Association of Ports and Harbours' (IAPH) World Ports Climate Initiative, has released bunker checklists as well as instructions on safe LNG bunkering processes. Despite all this, a minor error during the process in which the human factor plays an important role can lead to catastrophic results. In this context, human reliability analysis is essential for the ship to ship LNG bunkering process.

3.2. Empirical analysis

The suggested hybrid technique is used for STS LNG Bunkering operations on board to execute HRA since there is always a possible threat to human life, the sea environment, and the cargo in these operations.

Step 1. Task analysis: In the first step, a detailed task analysis is performed in the light of STS LNG bunker checklist (IAPH, 2019), P&I club circulars, and expert opinions. As a result of that, the HTA of the process is created. Table 2 shows the HTA of the operation, which consists of four stages. These are the planning stage, pre-bunkering activities, and during and after bunkering activities.

<Table 2> is inserted here.

Step 2. Scenario definition: In the scenario considered for the study, the STS LNG bunkering process was carried out in the morning hours in the Singapore anchorage area. According to the scenario, 3,000 cubic meters of LNG were transferred to the oil tanker ship. The person in charge of bunker transfer was sufficiently rested. Weather conditions were suitable for the operation. The sky was blue, and the wind speed was around 4-6 knots with a light breeze.

Step 3. GTT selection: A survey was applied to five maritime experts in the study, which benefited from expert opinions. Marine experts consist of DPAs (Designated Person Ashore) and chief engineers who are well-versed in the STS LNG bunkering operation and familiar with the process. First, maritime experts were asked to designate a GTT for each sub-task according to the HTA. Then, the experts were allowed to reach a consensus on the GTT of each sub-task. By all these, the GTT nominated by the experts is shown in Table 3.

Step 4. EPC/s selection: Similarly, the EPCs for each sub-task were assigned by the consensus of maritime experts. Single or more than one EPCs were selected from among the thirty-eight EPCs defined for HEART, which have the ability to increase the probability of human error. The EPCs determined by experts are shown in Table 3.

<Table 3> is inserted here.

Step 5. APOA calculation: According to Table 3, most sub-tasks have more than one EPC, and it is necessary to calculate APOA accordingly. This way, each EPC's effect, namely its weight, is detected. In this context, the D-S evidence theory is utilised to calculate the APOA and combine the evaluations of five maritime experts. Experts may have different attitudes towards EPCs depending on their experience and knowledge. This situation leads to conflicts between them, as described in Section 2.2.

Table 4 contains the conflict coefficients for sub-task 1.1, and it is understood that there are conflicts among the experts. Therefore, it is more appropriate to use the modified D-S evidence theory instead of the traditional D-S evidence theory.

<Table 4> is inserted here.

In order to deal with the aforementioned conflict, a modified D-S evidence theory is used during the APOA calculation, and experts are asked to assess the EPCs of each task in accordance with the 9-point scale. According to the scale, 0.1 represents the lowest efficiency, and the efficiency of EPC increases to 0.9 (Zhou et al., 2019). Judgments from experts are assumed to be pieces of evidence. Therefore, pieces of evidence from marine experts are combined using equations 10-15. Thus, the opinions of five different experts are brought together by considering the conflicts. Table 5 indicates the EPC weights of each sub-task.

<Table 5> is inserted here.

Step 6. HEP calculation: After the APOA calculations of the EPCs, the HEP values for the STS LNG bunkering operation are obtained via equation 16. The HEPs calculated for the entire sub-tasks are shown in Table 5 as well.

In addition, sub-task 1.1 is chosen as an example to give a detailed calculation of the modified D-S evidence theory implemented to fuse the views of five maritime experts for the APOA calculation and calculation of HEP. The selected EPCs, each result obtained from the equations used in the fusion process, and the result of the HEP calculation can be seen in Table 6.

<Table 6> is inserted here.

Step 7. Reliability assessment: To evaluate human reliability for STS LNG bunkering operation, the total HEP value should be determined. Considering the relationship between main tasks and sub-tasks, the notations given in Table 1 are utilised. According to the agreement between the experts, all 15 sub-tasks must be adequately performed in order to complete the first main task successfully. It indicates that the system is serial. On the other hand, it is identified that 15 sub-tasks had a high dependency, and the total HEP value is 3.70E-01. Accordingly, for the second main task, it is found that the system is serial, and there is a high dependency between the sub-tasks. Hence, the total HEP for the second main task is calculated as 4.02E-01. The third main task has nine sub-tasks, and if conservatively assumed that any of them fails, then the third main task fails (serial system). Since these nine sub-tasks are highly dependent on each other, the HEP of the third main task is assigned the maximum value of

the nine sub-tasks, that is, 3.54E-01. Finally, the total HEP for the fourth main task is found as 3.40E-01 (serial system-high dependency). The situation between the four main tasks is considered to calculate the final total HEP value for the STS LNG bunkering process. In this context, failure of one of the four steps means that the operation cannot be performed, so the system is serial. In this context, the final HEP value is 4.02E-01 as there is a high dependency between them. Finally, with the help of the formula R (t) = 1-F (t), which expresses the relationship between failure/error and reliability, human reliability for the operation is found to be 5.98E-01.

As in many studies, Park and Paik (2022) and Gerbec and Aneziris (2022) state that LNG bunkering involves various risks. Therefore, they analyse the risks at different points in the process. Lee et al. (2021) emphasized in their research that the STS method is the most preferred method among the optimal LNG bunkering methods for shipyard safety. On the other hand, Stokes et al. (2013) draw attention to the importance of the human factor in the LNG bunkering process and state that it is a subject that should be investigated. Fan et al. (2022) evaluate human performance for LNG bunkering, taking into account the safety philosophical factors of LNG bunkering companies. Accordingly, this paper considers the tasks to be implemented during the ship to ship LNG bunkering process, which includes various hazards. In this respect, it determines the overall human reliability of the process.

3.3. Findings and extended discussions

In view of the results of an extended D-S evidence fusion HEART approach, it can be said that the human reliability level (5.98E-01) is unsatisfactory. According to the human error probability range in the context control model, the choice of the following action is ascertained by careless characteristics of the situation, which is due to time limitation, operator inexperience, insufficient planning, etc. This situation leads to the emergence of action failures and cognitive failures due to incorrect observations or diagnoses. So the human error probability (4.02E-01) is above normal (Hollnagel 1998). To understand the process deficiency, sub-tasks with the highest HEP are discussed. In light of Figure 2, sub-task 1.7 (Communicate and agree on a contingency plan and emergency response plan to all parties involved in the bunkering operation, including the planned emergency response team) has the highest HEP value (3.70E-01) since LNG bunkering operations have specific risks and hazards.

<Figure 2> is inserted here.

Miscommunication of critical information between the parties, inadequate operations management by the person in charge, and poor safety culture in the organisation are just a few of the root causes that might lead to an error when completing this task. Therefore, the ship crew and the other parties (LNG bunker vessel and shore parties) are required to agree on an emergency and contingency preparation and plan. The emergency plan should be based on a comprehensive assessment of the hazards inherent in the workplace and the potential repercussions of an emergency resulting from these hazards. At this point, both an internal and external emergency plan should be established, including task distributions, alarm systems, communication channels, training, and possible dangers of LNG (Aneziris et al., 2021). Sub-task 1.15 (Review all bunkering procedures and carry out the ship to ship LNG bunker safety checklist with LNG bunker vessel) has the second-highest HEP (3.38E-01). Information exchange is the main reason for high HEP. This stage is critical to avoiding accidents during the fuel transfer operation between two vessels unfamiliar with one another from a technical and specific aspect. The LNG bunkering vessel and the LNG-fuelled ship exchange information and achieve agreements on safety-related concerns during the bunker transfer planning stage, which is a critical component of LNG bunkering. Due to commercial pressures in the maritime industry, fuel operations are frequently requested to be completed immediately, and checklists developed for ship officers under the ISM Code are commonly perceived as paperwork or extra effort. It is critical to review the properly signed checklists at specified intervals and periods. As a result, it is vital to rigorously apply the IAPH-developed standard ship to ship bunker checklist throughout operations (IAPH, 2019).

In the pre-bunkering activities, sub-task 2.8 (Carry out adequate supervision of the bunker operation by responsible officers is in place, both on the ship and at the LNG bunker vessel) has the highest HEP, which is 4.02E-01. The main reason for that failure could be a lack of proper training and experience for the person in charge. The appropriate level of training and expertise of all individuals engaging in LNG bunkering operations is critical. This will aid in avoiding the possibility of complacency and control work and rest hours to minimise fatigue during the workday. In addition, the crew should be thoroughly knowledgeable about the equipment, systems, and onboard procedures. In addition, providing specific operational familiarisation training on each ship that carries out LNG bunker operations can contribute to the safe execution of this task. The sub-task 2.39 (Carry out information exchange about pre-cooling, inerting, cooling down, vapour management, rates of transfer during the initial, bulk, topping stage, and filling sequence) has the second highest HEP value with 2.64E-01. Miscommunications of essential operation phases are a significant cause of failure and an increased probability of human error. In addition, inadequate experience and risk acceptance may cause errors in performing this task. Preparation for this task should include exchanging information between experienced officers and compliance with national and international rules. LNG fuel has certain features related to its chemical composition; for example, the temperature is a critical factor, as heated LNG evaporates rapidly. On the other hand, the initial loading rate, topping rate, and vapour management are also critical considerations. Before starting the operation, discussing some critical stages, exchanging information, and agreeing on how to carry it out is necessary. Pre-cooling, inerting, cooling down, vapour management, transfer rates during the initial, bulk, topping stage, and filling sequence are the critical stages of the bunkering operation. Both ships' LNG transfer systems should be pre-cooled to provide a homogeneous temperature distribution throughout the system, performed using nitrogen or LNG. This task involves risks such as cryogenic hazards, oxygen introduction into restricted spaces, and boil-off gas (Podimatas, 2020). Sub-task 2.14 (Maintain an active deck watch on the ship. Maintain an effective LNG bunker watch, both on board and on board the LNG bunker) has the third-highest HEP (2.33E-01) in the pre-bunkering activities. While a compelling deck watch eliminates the hazards that may arise during the STS LNG operation, on the other hand, with a persuasive LNG bunker watch, emergencies such as possible overflow and leakage can be detected beforehand. Due to commercial considerations and the absence of adequate time on ships, numerous operations (provision supply, water/oil supply, and crew change) are conducted simultaneously during bunkering operations. It is recommended not to carry out any simultaneous operation during the LNG fuel operation, and if necessary, necessary controls and risk assessments should be made. The critical element is that the LNG bunkering watchman should have no other duties than the operation. Before the bunkering operation, authorised personnel should identify roles and responsibilities, and deck watch and bunker watch schedules should be designed to ensure continuous monitoring of all processes. A constant deck watch should be kept for mooring lines, dropped anchors, fenders, and simultaneous operations. As mentioned in this description, this area is to be continuously supervised by a watchman entirely independent of the other deck watches and is planned to ensure the operation's safety. The LNG bunker watch is constantly cautious about LNG hoses, LNG manifolds, and LNG bunker controls (IAPH, 2019).

According to Figure 2, sub-task 3.1 (Agreed on starting temperatures, starting pressures, and available tank capacity) has the highest HEP (3.54E-01), whereas sub-task 3.3 (Agreed maximums and minimums (pressures during bunkering, pressures in the LNG bunker tanks, temperatures of the LNG, filling limit of the LNG bunker tanks)) has the second-highest HEP (1.47E-01) during the bunkering operation. Thus, these two tasks are closely linked and critical during the bunkering operation. Inadequate operations management by the supervisor, task planning, and briefing among the parties may lead to failure to exchange necessary information. Knowing the maximum and minimum pressure values is essential to reach normal operational parameters after the initial loading is started safely and everything is checked according to the checklist. On the other hand, continuous monitoring of these parameters is a reliable way to prevent potential overflow or leakage. The LNG loading rate should be reduced when approaching the topping-off level, and the LNG bunker vessel should be notified regarding the pre-agreement. Before initiating fuel operation, it is critical to verify that the operation proceeds safely by minimising manifold pressure and loading rate. Determining the initial temperature is also critical in this process to ensure a homogeneous temperature. Therefore, all parties should exchange information regarding the initial temperature, initial pressure, and tank capacity. Problems caused during this process may result in LNG leakage, overflow, or rapid evaporation at the beginning of the bunker transfer.

Sub-task 4.4 (Inert the bunker transfer pipeline and hose with nitrogen prior to the disconnection), in the phase after bunkering activities, has the highest HEP value (3,40E-01). In order to properly disconnect the bunker transfer pipeline and hose, nitrogen should be supplied into the system to prevent the explosive mixture. There could be a significant amount of cold vapour present, which could be inhaled. Extreme precautions should be maintained when disconnecting because frostbite can be caused by cold vapours or pipelines, among other things. As a result, various factors may contribute to the failure to complete this task successfully. For example, inadequate training and experience on the part of the person in charge may result in specific errors in executing this task. In the same way, fatigue and negligence could be identified as contributing factors. Sub-task 4.3 (Check All pressure release valves and vents to prevent potential over pressurisation) has the second-highest HEP (1.44E-01) during post-bunkering activities. Once bunkering transfer is complete, bunker pipelines and hoses should be drained and stripped to avoid the possibility of over-pressurization. The pressure in the pipeline and vents can spread vapour around during the hose disconnection, which can be inhaled and harm human health and ship equipment. However, negligence, inadequate personnel, and a lack of sleep could result in errors and even catastrophes when carrying out this task. Therefore, performing this operation by experienced personnel will prevent possible mistakes.

4. Conclusion

LNG is emerging as the preferred future fuel in many industries due to its higher efficiencies and fewer environmental concerns. There has been a significant rise in the transportation, storage, and use of LNG as a fuel across the globe. Nevertheless, the fact that LNG is a cryogenic fluid with vapour dispersion properties and is hence highly combustible brings numerous health and safety challenges. During LNG ship to ship bunkering, the potential accident may cause catastrophic results such as severe fatality, or total loss of vessel and cargo. In this context, human reliability analysis is paramount to enhancing safety. This paper proposes a conceptual framework for systematically assessing human reliability for STS LNG bunkering operational stages under an extended D-S evidence fusion HEART approach. The novelty of the article is that it is considered the first research for the HRA operation on the topic of the ship to ship LNG bunkering. In addition, some limitations are overcome with an extended D-S evidence fusion HEART methodology. Although HEART is a practical method for human reliability analysis, it may face the problem of combining multiple experts, such as selecting multiple EPCs and assigning different weights to EPCs. The D-S evidence fusion theory is used to overcome this situation, which considers vague, imprecise, and incomplete information. The D-S evidence fusion theory accepts the information obtained from each expert as a piece of evidence and provides the process of combining the evidence. This method provides HEART practitioners with a robust solution for determining APOA.

In view of the findings, human reliability is found to be 5.98E-01, which is reasonable but not at the desired level for the process. In this case, it can be said that human performance is based on limited planning, and a more or less known procedure is followed. On the other hand, distinctive features of the tasks performed (such as time constraints or incomplete understanding of the task) may impact the successful completion of the task. In this context, the operator can be guided by his habits and experience. Careless characteristics of the situation ascertain the choice of the following action due to human-oriented errors. Therefore, human reliability should be increased. Potential root causes of the human errors in the operation are ascertained, and the highest HEP values are discussed in the paper. Besides its robust theoretical background, the paper's findings provide a ground-breaking way to improve safety in LNG STS bunkering operations, minimise the risk to life and property, and avoid accidents such as overflowing, leakage, fire, and explosions. Future research will handle data derivation and uncertainty in probabilistic reliability assessment (PRA) under a simulation environment.

Nomenclature

$\overline{\text{APOA}}$	Integrated APOA
APOA	Assess the Proportion of Effect
BPA	Basic Probability Assignment
CREAM	Cognitive Reliability and Error Analysis Method
CO2	Carbon Dioxide
Crd	Credibility
DNV-GL	Det Norske Veritas – Germanischer Lloyd
DPA	Designated Person Ashore
D–S	Dempster-Shafer
EPC	Error Producing Condition
FOD	Frame of Discernment
GEP	Generic Error Probability

GHG	Greenhouse Gas
GTT	Generic Task Type
HEART	Human Error Assessment and Reduction Technique
HEP	Human Error Probability
HFACS	Human Factors Analysis and Classification System
HRA	Human Reliability Analysis
HTA	Hierarchical Task Analysis
IAPH	International Association of Ports and Harbours
IGF Code	International Code of Safety for Ships Operating Using on Gases or Other Low-Flashpoint Fuels
IGU	International Gas Union
IMO	International Maritime Organization
ISM	International Safety Management
k	Conflict Coefficient
LNG	Liquid Natural Gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MEPC	Marine Environment Protection Committee
NOx	Nitrogen oxides
P&I	Protection and Indemnity Insurance
PM	Particular Matter
PRA	Probabilistic Reliability Assessment
SLIM	Success Likelihood Index Method
SMS	Safety Management System
SO_2	Sulphur Oxide
STCW	International Convention on Standards of Training, Certification and Watchkeeping for Seafarers
STS	Ship to Ship
Θ	Frame of Discernment

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A human reliability analysis for ship to ship LNG bunkering process under D-S evidence fusion HEART approach.

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Abstract

LNG (Liquid Natural Gas) ship to ship bunkering process is quite a new concept for the maritime industry since the usage of LNG has been increasing worldwide. The LNG bunkering process poses a high risk due to human errors, while a minor error may be catastrophic. The expectation of the ship`s crew is to carry out operations without any errors. Therefore, human reliability analysis (HRA) is paramount to improving operational safety during the ship to ship LNG bunkering process. In this context, this paper performs a systematic HRA under the D–S (Dempster-Shafer) evidence fusion-based HEART (human error assessment and reduction technique) approach. While the HEART quantifies human error for the tasks being performed, the extended D-S evidence fusion deals with the limitation of APOA (assessing the proportion of effect) calculation since it significantly relies on evaluating a single rater. The finding shows that human reliability for the ship to ship LNG bunkering process is 5.98E-01 and reasonable, but not at the desired level. The paper`s outcomes will contribute to the utmost for LNG ship operators, safety inspectors, and ship owners to establish a safe and efficient ship to ship LNG bunkering process and minimise human error-based accidents.

Keywords: Human reliability, D-S evidence fusion theory, HEART, LNG bunkering process.

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1. Introduction

The world's marine transportation sector has already taken operational and technical strategies to limit greenhouse gas emissions (GHG). With MARPOL (International Convention for the Prevention of Pollution from Ships) Annex VI, which took effect on 1 January 2013, the IMO (International Maritime Organization) introduced a new strategy for reducing carbon emissions and preserving ship energy efficiency (IMO, 2017a). In this context, the Marine Environment Protection Committee (MEPC 72) of the International Maritime Organization (IMO) established a more strict emission reduction strategy for greenhouse gases (GHG) and proposed a reduction of GHG emissions from international shipping by at least 50 per cent annually by 2050 (IMO, 2018). Energy efficiency has already become a necessity in maritime transportation as a result of higher marine fuel costs, increases in taxes, and air pollution requirements. To comply with the IMO's targets, it is essential to adopt and encourage new technologies, alternative fuels, and alternative energy sources on all ships worldwide to reduce ship-related greenhouse gas emissions (Faber et al., 2019). The IMO declared to decrease the sulphur content of ships' fuel oil to 0.5 per cent (from 3.5 per cent) on January 1, 2020, in line with European regulations (IMO, 2018). This resolution will likely substantially affect ship fuel use and stimulate demand for alternative fuels. Nowadays, alternative fuels such as bio methanol (Faber et al., 2019), ammonia (Bicer and Dincer, 2018), dimethyl ether (Juan-Alcañiz et al., 2010), biodiesel (Mohd Noor et al., 2018), fuel cells (Van Biert et al., 2016) and gaseous fuels including LNG (Liquefied Natural Gas) (Burel et al., 2013) are indeed offered for maritime transportation.

On the other hand, in the process of introducing and using alternative fuels, there are many difficulties, such as determining the emissions of fuels, their prices, availability of supply, the technical suitability of ships, the structural suitability of ports, and expertise (Prussi et al., 2021). New technological systems introduce new safety concerns, and human interaction is still required (Fan et al., 2022). Human reliability, therefore, plays a crucial role in improving shipboard safety. Due to the strict enforcement of environmental restrictions, ship owners are investigating using clean alternative fuels to reduce emissions from ships while maintaining within the prescribed limit. LNG was determined to be more favourable than other alternative fuels and began to be used as a ship fuel (Prussi et al., 2021). Furthermore, the International Gas Union's 2021 report states that using LNG as a ship fuel is a feasible alternative for preventing air pollution and adhering to strict emission regulations. LNG is now the most cost-effective and readily available technology for reducing the environmental impact of maritime shipping and preserving air quality on a large scale (IGU, 2021). According to Sphera, greenhouse gas (GHG) emissions reductions of up to 23% are now possible by using LNG as a marine fuel, based on the new equipment and technology adopted (Sphera, 2021). Environmental impacts and reasonable price conditions make LNG fuel a more sustainable alternative than conventional fuels (Prussi et al., 2021). There are currently 572 LNG ships (LNG as a cargo) in operation, according to the IGU (International Gas Union) 2021 report (IGU, 2021). Transportation of LNG as cargo is widespread; therefore, both ship owners and crew members are familiar with LNG-carrying ships' operations due to regulations, specific inspections, and established safety culture. In the IGU 2021 report, it is stated that the number of LNG bunkering vessels is 22, the LNG terminals and ports are 44, and most of them are operated in Europe (IGU, 2021). At the same time, according to the 2021 DNV GL reports, it is stated that the number of ships using LNG fuel is 198. Due to the beneficial environmental consequences and benefits associated with safe processes, studies have highlighted that the number of ships utilising LNG fuel and facilities delivering LNG fuel will increase in the future (DNV, 2021; Sun et al., 2017). Considering all this, the performance of the ship crew during the ship to ship LNG bunkering process becomes a very critical issue.

1.1. Literature reviewing

LNG is a natural gas that inherently contains fire and explosion hazards, so the bunkering, storage, and transportation of LNG fuel is an operation that requires great care. In recent years, there has been an increase in literature on LNG bunkering, with most of this literature comprising risk assessment studies (Aneziris et al., 2021; Fu et al. 2016; Noh et al., 2014). For instance, Gerbec and Aneziris (2022) performed a risk assessment on uncertainties in failure rates of bunkering arms and hoses for LNG bunkering. Fan et al. (2021) conducted a risk assessment to generate a data set of dynamic risk assessments for LNG bunkering during simultaneous operation. Lee et al. (2021) investigated the optimal LNG bunkering methods for shipyard safety using the analytic hierarchy process. In the study, they concluded that the ship to ship bunkering was chosen with the highest weight among the LNG bunkering methods by experts. Iannaccone et al. (2021) conducted risk assessments for the passenger's vessels by developing possible scenarios for port operations during the LNG bunkering operation. Jeong et al. (2018) utilised a probabilistic risk assessment strategy to establish the safe exclusion zone surrounding LNG bunkering stations based on the determined LNG bunkering risk. Similarly, Park and Paik (2022) discussed the safe zone design during truck to ship bunkering.

In the literature, studies have also focused on the economic benefits and economic analysis of ships using LNG fuel (Lee et al., 2020), LNG bunkering facilities (Calderón et al., 2016; Park and Park, 2019), environmental effects of LNG fuel and reducing emissions, feasibility, and economic impact (Schinas and Butler, 2016). Various studies examined safety concerns associated with LNG operations (Animah and Shafiee , 2020; Sultana et al., 2019; Lee et al., 2015; Alderman, 2005), specifically in terms of LNG storage and bunkering facilities (Aneziris et al., 2020), safety assessment of alternative technologies used in LNG bunkering (Iannaccone et al., 2019) and resilience assessment of LNG bunkering with a decision support system (Vairo et al., 2020).

There are also some studies on human errors. Fan et al. (2022) analysed the human error probabilities for LNG bunkering operation with a quantitative method Fuzzy Bayesian CREAM model. In this study, HEPs were estimated by evaluating safety philosophical factors. Stokes et al. (2013) performed a study about the human factor in LNG bunkering operations and stated that the competencies of crew and staff are essential to enhance safety. When investigating human error and reliability in LNG bunkering operations, it has been revealed that there is insufficient research in this area.

These studies confirm the significance of the human element and demonstrate that human error has been the leading cause of accidents. There are different LNG bunkering operations, including ship-to-ship, truck-to-ship, shore-to-ship, etc. Consequently, each distinct type of operation involves its hazards and control measures. To address this gap in the literature, the purpose of this study was to evaluate the importance of human reliability in LNG ship bunkering. Ship crews perform critical tasks during the ship to ship LNG bunkering process. To successfully complete the process, it is essential to carry out the tasks without making errors. In this context, the human factor is paramount to enhancing process safety and minimising potential accidents.

According to the statistics, more than 80 per cent of maritime accidents are due to human error (Liu et al., 2021; Khan et al., 2020). Human errors' contribution to maritime and offshore industries have been widely discussed in different topics such as maintenance in petrochemical plants (Rozuhan et al., 2020), floating offshore structures (Abaei et al., 2019; Akyuz and Celik, 2016), critical shipboard operations (Erdem and Akyuz, 2021; Kandemir et al., 2019; Akyuz, 2016), and ship collision (Arici et al, 2020; Aydin et al., 2021a). Marine and offshore safety practitioners encourage additional study publications as human error-related accidents continue to occur. In addition, HRA techniques using expert judgments such as Cognitive Reliability and Error Analysis Method (CREAM) (Elidolu et al., 2022; Aydin et al., 2021b), Success Likelihood Index Method (SLIM) (Uflaz et al., 2022), Human Factors Analysis and Classification System (HFACS) (Qiao et al., 2020), HEART (Akyuz et al., 2018; Islam et al., 2017) are generally adopted in human reliability analysis studies in the maritime literature. On the other hand, techniques such as fuzzy logic (Ahn and Kurt, 2020), analytical hierarchy process (Akyuz and Celik, 2015a), evidential reasoning (Wu et al., 2017), Bayesian network (Yang et al., 2019) are integrated into the methodologies in order to analyse the studies more effortlessly and to overcome some uncertainties. The D-S evidence theory is preferred to fuse expert opinions in this paper. In this context, the different effect rates determined by the multiple experts for the same EPCs are combined with the D-S evidence theory. Thus, the problem of combining the opinions of multiple experts can be solved.

1.2. LNG Bunkering fundamentals

Even though conventional fuel bunkering has become routine, it remains a critical and dangerous job. From this point of view, LNG bunkering is a relatively new bunkering operation, and it exposes the ship to several threats due to the variety of approaches used. Consequently, both the LNG bunker and LNG-fuelled vessels should develop a strategy to ensure a safe operation. Authorised persons should conduct the necessary controls in compliance with all existing international and national regulations. Furthermore, it is essential to prevent human error by ensuring that all personnel involved in the LNG bunkering operation meet the minimum training standards. The minimum training requirements for seafarers taking part in LNG bunkering operations are essentially covered by Regulation V/3 of the STCW (International Convention on Standards of Training, Certification, and Watchkeeping for Seafarers) Code and detailed in Section A-V/3 of the STCW Code (IMO, 2015). The person in charge should be familiar with the risks of the process of LNG bunkering (Fan et al., 2021) , the operational rules (Wang and Notteboom, 2015) and systems, the requirements of the ship to ship operation, possible emergency procedures for fire and explosion (Aneziris et al., 2014; Mokhatab et al., 2013). In addition to this knowledge, the adequate rest of key personnel is crucial for preventing potential dangers, particularly with regard to human element issues (Stokes et al., 2013).

All relevant stakeholders in the LNG bunkering are expected to be familiar with the ship's operational stages during the bunkering, which may vary depending on the ship's structural and technical features and the location of the operation. Humans play a role in maritime facilities' design, operations, maintenance, and administration. As a result of this considerable involvement, human factors are commonly identified as a reason for marine accidents. In order to preserve safety, the human aspect must be considered at all stages of any type of bunkering operation. Traditional bunkering is a frequent activity on board a ship that has been the cause of multiple accidents in the past due to human errors such as the improper setting of valves, insufficient tank monitoring, malfunction of valves, complacency, high workload, fatigue, poor communication, and unfamiliarity (UKP&I, 2018). It is also critical that bunkering operations are well planned throughout and that the essential risk control procedures are in place to prevent an incident and facilitate an efficient reaction. There are still some undesirable accidents in bunkering operations today (such as overflow, leakage, sea pollution, etc.). Like conventional refuelling bunkering, LNG bunkering is a substantial threat that must be carried out properly due to its inherent dangers. The operation of LNG fuel is a recent process with limited experience; for this reason, many policy-making and supervisory organisations have developed procedures and operational checklists for shore and ship staff. Captains, chief engineers, officers, crew members, and other workers involved in the operation are expected to acquire training consistent with the STCW Code's requirements for their training and qualifications. Consequently, the studies to be conducted in this field should contribute to the formation of a risk profile, the calculation of human errors, the identification of risks and precautions, and the determination of the probability of accidents in the sector, all of which will contribute to the safety of operations.

Since the number of ships using LNG fuel and facilities providing LNG fuel has been growing gradually, analysing the human reliability of ship to ship LNG bunkering process has remained limited. Previous research has not investigated human reliability analysis (HRA) in LNG ship to ship bunkering. This research seeks to obtain human error probability (HEP), which will help address the aforementioned gaps and improve the safety level of LNG bunkering.

In the view above, although there is limited research on D-S-based HEART methodology in the maritime industry, there is a lack of research that directly deals with human error and the reliability of the ship to ship LNG bunkering process. Therefore, this paper remedies the gap by performing a systematic HRA under an extended D-S evidence fusion HEART approach to enhance safety and minimise human error in LNG-fuelled ships. In this context, the paper is organised as follows. Section 1 gives a short explanation of why the study was done, as well as a detailed review of the literature and a look at how LNG is moved by sea. Section 2 introduces methodologies. Section 3 performs HRA for the ship to ship LNG bunkering. Finally, the conclusion regarding the subject is mentioned and recommendations for future research are provided in Section 4.

2. Methodology

2.1. HEART

Human error assessment and reduction technique (HEART) was introduced to conduct an empirical human error and reliability prediction (Williams, 1988). The method provides a practical tool to estimate HEP for a specific task in the operational system. HEART is a modelling tool applied in safety and reliability analysis in many industries, such as railways (Wang et al., 2018), nuclear power plants (Kirwan et al., 2005), the business world (Evans et al., 2019a) and occupational health (Aliabadi, 2021). In cases where human error data is scarce, it is very challenging to estimate HEP by applying stochastic models such as Bayesian networks or Markov chains. Also, many of the other HRA methodologies available are limited in their ability to reveal all significant aspects of the human factor. Therefore, it is more reasonable to use a technique such as HEART that allows the evaluation of human performance as a whole. HEART is a robust and straightforward tool that evaluates human tasks to calculate the HEP value. There are two fundamental parameters to calculate HEP; generic task type (GTT) and error-producing condition (EPC) (Deacon et al., 2013; Liu and Zhang, 2020; Noroozi et al., 2014). The GTT assists users in capturing appropriate tasks under HRA and defines the generic error probability (GEP) value. The EPC defines the performance shaping factor which influences the probability of human error in the associated task. As a result, the data set covers multiple HEP values derived from different domains such as nuclear power plants, the petrochemical industry, offshore platforms, the service industry, etc. (Williams, 1988). In the method, there are nine GTTs defined and those are addressed to GEP values. After that, the EPC is determined by experts. The EPCs are significant factors such as operator experience, limited time, familiarity, fatigue, noise level, etc., which may significantly affect human performance and increase HEP. There are thirty-eight different EPCs assigned in the original HEART approach (Williams, 1988) and generally these EPCs are considered in studies (Navas et al., 2022; Aliabadi, 2021; Evans et al. 2019b).

2.2. D-S evidence fusion theory

The D-S evidence theory is a method of analysis for data representation and reasoning purposes, considering uncertain, imprecise, and incomplete information (Sentz and Ferson, 2002). The method was first presented by Dempster (Dempster, 1967) and then expanded by Shafer (Shafer, 1976). The theory is a powerful mathematical framework used today when it comes to situations such as uncertainty (Sezer et al., 2022), multi-source information fusion (Li et al., 2021; Zhu and Xiao, 2021) and decision-making with uncertain information (Liu and Zhang, 2020).

Let Θ be the universal set titled Frame of discernment (FOD). This set contains all possible states $\{H_1, H_2, \ldots, H_n\}$. In addition, 2^Θ represents the power set of the versatile collection. Therefore, each element of 2^Θ has a value in the range of [0,1].

$$\Theta = \{H_1, H_2, \ldots, H_n\} \tag{1}$$

$$2^\Theta = \left\{\emptyset, \{H_1\}, \{H_2\}, \ldots \{H_n\}, \{H_1 \cup H_2\}, \ldots, \{H_1 \cup H_2 \cup \ldots H_i\}, \ldots \{H_1 \cup H_2 \cup \ldots H_n\}\right\} \tag{2}$$

The basic probability assignment (BPA) function refers to the amount of data obtained from different sources, and Θ has a relationship with each power set. The representation of the BPA function and the assumptions it should provide are as follows.

$$m: 2^{\Theta} \rightarrow [0,1] \tag{3}$$

$$m(\emptyset) = 0 \tag{4}$$

$$\sum_{A \in 2^{\Theta}} m(A) = 1 \tag{5}$$

The expression $\emptyset$ in equation 4 symbolises the empty set and means there is no possibility for the relevant parameter to be found outside FOD. An in Equation 5 denotes any power set of FOD and is called the focal element. The mass function m(A) shows the extent to which the evidence backs A.

D-S evidence theory demonstrates the rule of combining data from independent and various sources. According to this rule, when more than one mass function, BPA, is given from the same FOD, it can be combined. The Dempster combination rule is as follows:

$$m_{12}(A) = \begin{cases} \frac{\sum_{B \cap C \neq \emptyset} m_1(B) m_2(C)}{1-k}, A \neq \emptyset \\ 0, \ A = \emptyset \end{cases} \tag{6}$$

$$k = \sum_{B \cap C = \emptyset} m_1(B) m_2(C) \tag{7}$$

m_1 and m_2 are two independent BPA functions. Thanks to Dempster's rule of combination, the total belief level of the two functions is determined. m_{12} stands for combined BPA. k is expressed as the conflict coefficient and depicts the conflict between m_1 and m_2.

The D-S evidence theory is adapted according to HEART as follows. If we assume that the number of experts making EPC evaluations is n, this can be shown as $E = \{e_i | i = 1, 2, \dots n\}$. In this study, FOD comprises thirty-eight EPCs. Assuming an expert selects one or more EPCs, the FOD can be a set like $\Theta = \{\mathrm{EPC}_t | 1, 2, \dots 38\}$. Let's think that EPCs $= \{\mathrm{EPC}_l, EPC_m\}$ are the focal elements contained in FOD and procured from experts in e_q and e_p $\left(p \neq q; p, q \in (1, n)\right)$. These are pieces of evidence to which the fusing process was applied. It satisfies equation 5 $\sum_{l=1}^{38} e_p(EPC_l) = 1; \sum_{m=1}^{38} e_q(EPC_m) = 1$ (Zhou et al., 2019).

Pieces of evidence from different sources can be brought together with the help of the Dempster combination rule (Wang et al., 2021). The customisation of the combining rule in Equation 6 for HEART is as follows.

$$e_{p,q} = \begin{cases} \dfrac{\sum_{EPC_l \cap EPC_m \neq \emptyset} e_p(EPC_l) e_q(EPC_m)}{1 - k_{(\mathrm{ep},\mathrm{eq})}}, A \neq \emptyset \\ 0, \qquad A = \emptyset \end{cases} \tag{8}$$

Where, k(e_p, e_q) is the coefficient of conflict between the evidence and expresses the extent of the disagreement between the experts and is denoted as:

$$k(e_p, e_q) = \sum_{EPC_l \cap EPC_m = \emptyset} e_p(EPC_l) e_q(EPC_m) \tag{9}$$

Zadeh observes that the Dempster combination rule leads to illogical conclusions when the evidence is highly conflicting. When k → 1, the evidence has a high conflict coefficient, which means unreasonable results can occur. Besides, in the case of $k = 1$, the Dempster combination rule cannot be used. A modified rule may be needed to solve these problems (Wang et al., 2021; Zadeh, 1984). This paper applies equations 10-15 to deal with the conflict coefficient problem (Zheng et al., 2017; Zhou et al., 2019).

In this context, the combining rule is applied with the help of cross-merging in the paper. First, similarity coefficients based on cosine similarity are calculated from the evidence obtained from experts (Chen and Zhang, 2021; Liang et al., 2016). e_p and e_q are two pieces of evidence, and the calculation of the similarity coefficient (sim (e_p, e_q)) between them is as follows:

$$sim(e_p, e_q) = \frac{\sum_{EPC_l \cap EPC_m \neq \emptyset} e_p(EPC_l) e_q(EPC_m)}{\sqrt{\left(\Sigma\left(e_p(EPC_l)\right)^2\right) . \left(\Sigma\left(e_q(EPC_m)\right)^2\right)}} \tag{10}$$

After determining the similarity coefficient of each pair of evidence, assuming that the number of evidence is n, the similarity matrix is created as in equation 11.

$$s = \begin{bmatrix} 0 & \mathrm{sim}_{(e_1,e_2)} & \cdots & \mathrm{sim}_{(e_1,e_n)} \\ \mathrm{sim}_{(e_2,e_1)} & 0 & \cdots & \mathrm{sim}_{(e_2,e_n)} \\ \cdots & \cdots & \cdots & \cdots \\ \mathrm{sim}_{(e_n,e_1)} & \mathrm{sim}_{(e_n,e_2)} & \cdots & 0 \end{bmatrix} \tag{11}$$

Then, the degree of support of the evidence is computed with the help of the degree of similarity. The sum of the similarity between the other evidence and the e_p indicates the degree of support of the e_p and is denoted as sup(e_p). The high level of similarity between one piece of evidence and other evidence leads to a high degree of support (Dong et al., 2011; Guo and Li, 2011). The degree of support for each piece of evidence is defined as follows.

$$\sup(e_p) = \sum_{q=1,q\neq p}^{n} sim(e_p, e_q) \quad (p = 1,2, \dots n) \tag{12}$$

The degree of support of evidence allows us to know about the reliability of the evidence (Guo and Li 2011). The credibility (Crd) of e_p is calculated by applying the normalisation process and is provided as follows.

$$Crd(e_p) = \frac{\sup(e_p)}{\sum_{p=1}^{n} \sup(e_p)} \quad (p = 1,2, \dots n) \tag{13}$$

The weighted average of the basic true distribution for each EPC is obtained using equation 14 after the credibility process, which expresses the relative importance of each piece of evidence, is completed. In the light of f equation 15, the weighted averages of the basic true distribution are normalised and the $\overline{APOA}$, which is the fused version of each EPC, is determined.

$$e_c(EPC_t) = \sum_{p=1}^{n} e_p(EPC_t).Crd(e_p) \quad (t = 1,2, \dots ,38) \tag{14}$$

$$\overline{APOA}_t = e(EPC_t) = \frac{e_c(EPC_t)^2}{\sum_{t=1}^{n} e_c(EPC_t)^2} \quad (t = 1,2, \dots ,38) \tag{15}$$

2.3. Integration of methodologies: An extended D-S evidence fusion HEART

Integration of D-S evidence theory into HEART to implement more accurate HRA in shipboard operations is delineated in the flow diagram in Figure 1.

<Figure 1> is inserted here.

According to Figure 1, firstly, task analysis is performed to detect the tasks of the process under consideration. Then the scenario is defined in order to know the process conditions. In light of all these, HEART, one of the human reliability analysis methods, is applied. Accordingly, the GTT and EPCs of each task are determined by the experts. Modified D-S evidence theory is carried out to fuse different EPC assessments from multiple experts. In this context, firstly, the similarity coefficients between the evidence derived by the experts are obtained (Eq. 10). The similarity matrix is defined by means of similarity coefficients (Eq. 11). With the help of the similarity matrix, the support degree of each expert is determined (Eq. 12). The credibility of each expert is specified by applying the normalization process to the support degree (Eq. 13). The credibility of each expert and the degree of belief in the EPC allows to obtain the basic true distribution of each EPC (Eq. 14). Finally, the basic true distributions of the EPCs are normalized to obtain the weight of each EPC, that is, the fused APOA value (Eq. 15). The original HEART method is used to find the HEP value of each task. Various notations are taken into account to determine the overall HEP value of the process. Details of the main steps of the approach are provided below.

Step 1. Task analysis: In the first step, the tasks of the activity are compiled by bringing them together. Task analysis is conducted in accordance with hierarchical task analysis (HTA), in which main tasks are separated into sub-tasks (Akyuz and Celik, 2015a; Shepherd, 2000). The tasks of the activity that must be completed successfully are considered. Thus wise, HEP values of main tasks and sub-tasks can be estimated.

Step 2. Scenario definition: In this step, instant situations are explained to account for various conditions such as physical working conditions, limitations of the operation, and the situations of the persons performing the task (Akyuz et al., 2018; Aydin et al., 2021). These conditions that affect human performance during the execution of each sub-task are quite substantial in determining GTT and EPC.

Step 3. GTT selection: This step aims to assign the most appropriate of the nine GTTs from A to M associated with each identified sub-task. The quantitative value, called GEP, of each specific task evaluated with the help of the GTT and determined by the experts, is detected (Kirwan and Gibson, 2008).

Step 4. EPC/s selection: After determining the GEP value of each sub-task, EPCs that enhance the probability of human error are included in the analysis process. The experts select the most suitable EPCs for the sub-tasks concerning the scenario. If the expert makes multiple selections among the EPCs identified for HEART, the APOA calculation is needed to assign the overall impact of the EPCs.

Step 5. APOA calculation: In the APOA calculation, the proportion of the EPC impact is determined. This paper adopts a modified D-S evidence theory instead of traditional APOA calculation. This improves the accuracy of the calculation for human reliability analysis by appointing the impact ratio of each EPC. Due to the selection of multiple EPC at this stage, multi-experts may assign different effect weights to evaluate EPCs. The problem of fusing multi-expert-based EPCs is solved in this step.

Step 6. HEP calculation: After determining the GEP, EPC, and $\overline{APOA}$ values for each sub-task, the HEP values of the sub-tasks can be calculated using the formula below (Williams, 1988).

$$\mathrm{HEP} = \mathrm{GEP} \times \left\{ \prod_t [(EPC_t - 1)\overline{APOA}_t + 1] \right\} \tag{16}$$

According to equation 16, EPC_t is the t^{th} $(\mathrm{t} = 1,2,3, \dots 38)$ EPC and $\overline{APOA}_t$ is the fused $\overline{APOA}$ value of EPC_t.

Step 7. Reliability assessment: After acquiring the HEP values of the sub-tasks, some notation can be considered to calculate the total HEP of all the tasks. Table 1 contains the notations mentioned (He et al. 2008).

<Table 1> is inserted here.

According to Table 1, the tasks of a system can be connected in parallel or in series. Failure of a sub-task can cause the system to fail. In this case, it is assumed that the tasks are connected in series. If a sub-task fails and the system continues to run, it is considered that the tasks are connected in parallel (Akyuz and Celik, 2015a). On the other hand, considering the dependency status of the sub-tasks of the system, the relevant formula is used.

Furthermore, the probability of a system operating without errors or failures is called reliability, and the equation $R(t) = 1 - F(t)$ is the formulation of this definition. $R(t)$ denotes reliability while $F(t)$ denotes failure probability (Akyuz and Celik, 2015b).

3. Human reliability analysis for ship to ship LNG bunkering.

This section performs an empirical HRA for the ship to ship LNG bunkering process to enhance operational safety levels and minimise potential risks in maritime transportation.

3.1. LNG as fuel onboard ship

For decades, the engines of LNG carriers have been powered by the natural boil-off of the LNG stored in their cargo tanks. During the LNG discharge and storage process, a portion of the LNG evaporates into the gas phase, which is typically referred to as boil-off gas and can be utilised as fuel (Sastre Buades, 2017). Installing LNG as a fuel on other types of vessels, however, requires the installation of new systems and equipment for burning, handling, and storing the LNG.

LNG effective countermeasures and operating procedures on the part of crews and management companies (UKP&I, 2019). The LNG is a cold, odourless, non-toxic, non-corrosive liquid with a low flashpoint and has a lower density than water kept at atmospheric pressure. LNG has the most considerable energy output of any hydrocarbon and is composed primarily of methane (often more significant than 80%), with some ethane mixes. Methane vapour liquefies at temperatures below -82°C and is stored at near atmospheric pressure at temperatures of approximately -162°C (Alderman, 2005; UKP&I, 2019). Gas and other low-flashpoint fuels are considered cleaner than different fuel types because they emit air pollutants such as SO_2 and PM at lower rates when burned (IMO, 2017b). The International Code of Safety for Ships Operating using Gases or Other Low-flashpoint Fuels (IGF Code), which was adopted by the International Maritime Organization (IMO) on January 1, 2017, established some targets and standards for the design, construction, and operation of ships operating on this type of fuel (IMO, 2017b). Ships that will refuel LNG within the scope of the IGF Code should fulfil specific design and feature requirements, and their operators should satisfy specific training and qualification requirements. Four LNG bunker supply options are available to LNG-fuelled ships using existing technology and equipment (UKP&I 2019): i.) Ship-to-ship (STS) LNG bunkering, ii.) Truck-to-ship LNG bunkering, iii.) Terminal-to-ship LNG bunkering, iv.) Containerized (portable) LNG tanks are used as fuel tanks.

All of those bunker delivery techniques involve unique regulations and equipment, and the STS bunkering method provides for more flexible terms and the delivery of more significant amounts of LNG (Arnet, 2014; EMSA, 2018; Jeong et al., 2018). Ship-to-ship LNG bunkering operations can take place in either port areas or the open sea and provide several operational advantages.

Ship-to-ship LNG bunkering can take place alongside facilities and at anchorages within port boundaries through the fuel hose. It is not conventional to conduct LNG bunkering operations while the ships are underway and should not be performed without all the appropriate STS mooring and fendering systems (EMSA, 2018; UKP&I, 2019). Although it is not extensively used in LNG bunkering, policymakers and companies that consume LNG fuel have established operational checklists due to the various hazards and risks associated with LNG. The Advisory Committee on LNG-Fuelled Vessels, organised in 2014 as part of The International Association of Ports and Harbours' (IAPH) World Ports Climate Initiative, has released bunker checklists as well as instructions on safe LNG bunkering processes. Despite all this, a minor error during the process in which the human factor plays an important role can lead to catastrophic results. In this context, human reliability analysis is essential for the ship to ship LNG bunkering process.

3.2. Empirical analysis

The suggested hybrid technique is used for STS LNG Bunkering operations on board to execute HRA since there is always a possible threat to human life, the sea environment, and the cargo in these operations.

Step 1. Task analysis: In the first step, a detailed task analysis is performed in the light of STS LNG bunker checklist (IAPH, 2019), P&I club circulars, and expert opinions. As a result of that, the HTA of the process is created. Table 2 shows the HTA of the operation, which consists of four stages. These are the planning stage, pre-bunkering activities, and during and after bunkering activities.

<Table 2> is inserted here.

Step 2. Scenario definition: In the scenario considered for the study, the STS LNG bunkering process was carried out in the morning hours in the Singapore anchorage area. According to the scenario, 3,000 cubic meters of LNG were transferred to the oil tanker ship. The person in charge of bunker transfer was sufficiently rested. Weather conditions were suitable for the operation. The sky was blue, and the wind speed was around 4-6 knots with a light breeze.

Step 3. GTT selection: A survey was applied to five maritime experts in the study, which benefited from expert opinions. Marine experts consist of DPAs (Designated Person Ashore) and chief engineers who are well-versed in the STS LNG bunkering operation and familiar with the process. First, maritime experts were asked to designate a GTT for each sub-task according to the HTA. Then, the experts were allowed to reach a consensus on the GTT of each sub-task. By all these, the GTT nominated by the experts is shown in Table 3.

Step 4. EPC/s selection: Similarly, the EPCs for each sub-task were assigned by the consensus of maritime experts. Single or more than one EPCs were selected from among the thirty-eight EPCs defined for HEART, which have the ability to increase the probability of human error. The EPCs determined by experts are shown in Table 3.

<Table 3> is inserted here.

Step 5. APOA calculation: According to Table 3, most sub-tasks have more than one EPC, and it is necessary to calculate APOA accordingly. This way, each EPC's effect, namely its weight, is detected. In this context, the D-S evidence theory is utilised to calculate the APOA and combine the evaluations of five maritime experts. Experts may have different attitudes towards EPCs depending on their experience and knowledge. This situation leads to conflicts between them, as described in Section 2.2.

Table 4 contains the conflict coefficients for sub-task 1.1, and it is understood that there are conflicts among the experts. Therefore, it is more appropriate to use the modified D-S evidence theory instead of the traditional D-S evidence theory.

<Table 4> is inserted here.

In order to deal with the aforementioned conflict, a modified D-S evidence theory is used during the APOA calculation, and experts are asked to assess the EPCs of each task in accordance with the 9-point scale. According to the scale, 0.1 represents the lowest efficiency, and the efficiency of EPC increases to 0.9 (Zhou et al., 2019). Judgments from experts are assumed to be pieces of evidence. Therefore, pieces of evidence from marine experts are combined using equations 10-15. Thus, the opinions of five different experts are brought together by considering the conflicts. Table 5 indicates the EPC weights of each sub-task.

<Table 5> is inserted here.

Step 6. HEP calculation: After the APOA calculations of the EPCs, the HEP values for the STS LNG bunkering operation are obtained via equation 16. The HEPs calculated for the entire sub-tasks are shown in Table 5 as well.

In addition, sub-task 1.1 is chosen as an example to give a detailed calculation of the modified D-S evidence theory implemented to fuse the views of five maritime experts for the APOA calculation and calculation of HEP. The selected EPCs, each result obtained from the equations used in the fusion process, and the result of the HEP calculation can be seen in Table 6.

<Table 6> is inserted here.

Step 7. Reliability assessment: To evaluate human reliability for STS LNG bunkering operation, the total HEP value should be determined. Considering the relationship between main tasks and sub-tasks, the notations given in Table 1 are utilised. According to the agreement between the experts, all 15 sub-tasks must be adequately performed in order to complete the first main task successfully. It indicates that the system is serial. On the other hand, it is identified that 15 sub-tasks had a high dependency, and the total HEP value is 3.70E-01. Accordingly, for the second main task, it is found that the system is serial, and there is a high dependency between the sub-tasks. Hence, the total HEP for the second main task is calculated as 4.02E-01. The third main task has nine sub-tasks, and if conservatively assumed that any of them fails, then the third main task fails (serial system). Since these nine sub-tasks are highly dependent on each other, the HEP of the third main task is assigned the maximum value of

the nine sub-tasks, that is, 3.54E-01. Finally, the total HEP for the fourth main task is found as 3.40E-01 (serial system-high dependency). The situation between the four main tasks is considered to calculate the final total HEP value for the STS LNG bunkering process. In this context, failure of one of the four steps means that the operation cannot be performed, so the system is serial. In this context, the final HEP value is 4.02E-01 as there is a high dependency between them. Finally, with the help of the formula R (t) = 1-F (t), which expresses the relationship between failure/error and reliability, human reliability for the operation is found to be 5.98E-01.

As in many studies, Park and Paik (2022) and Gerbec and Aneziris (2022) state that LNG bunkering involves various risks. Therefore, they analyse the risks at different points in the process. Lee et al. (2021) emphasized in their research that the STS method is the most preferred method among the optimal LNG bunkering methods for shipyard safety. On the other hand, Stokes et al. (2013) draw attention to the importance of the human factor in the LNG bunkering process and state that it is a subject that should be investigated. Fan et al. (2022) evaluate human performance for LNG bunkering, taking into account the safety philosophical factors of LNG bunkering companies. Accordingly, this paper considers the tasks to be implemented during the ship to ship LNG bunkering process, which includes various hazards. In this respect, it determines the overall human reliability of the process.

3.3. Findings and extended discussions

In view of the results of an extended D-S evidence fusion HEART approach, it can be said that the human reliability level (5.98E-01) is unsatisfactory. According to the human error probability range in the context control model, the choice of the following action is ascertained by careless characteristics of the situation, which is due to time limitation, operator inexperience, insufficient planning, etc. This situation leads to the emergence of action failures and cognitive failures due to incorrect observations or diagnoses. So the human error probability (4.02E-01) is above normal (Hollnagel 1998). To understand the process deficiency, sub-tasks with the highest HEP are discussed. In light of Figure 2, sub-task 1.7 (Communicate and agree on a contingency plan and emergency response plan to all parties involved in the bunkering operation, including the planned emergency response team) has the highest HEP value (3.70E-01) since LNG bunkering operations have specific risks and hazards.

<Figure 2> is inserted here.

Miscommunication of critical information between the parties, inadequate operations management by the person in charge, and poor safety culture in the organisation are just a few of the root causes that might lead to an error when completing this task. Therefore, the ship crew and the other parties (LNG bunker vessel and shore parties) are required to agree on an emergency and contingency preparation and plan. The emergency plan should be based on a comprehensive assessment of the hazards inherent in the workplace and the potential repercussions of an emergency resulting from these hazards. At this point, both an internal and external emergency plan should be established, including task distributions, alarm systems, communication channels, training, and possible dangers of LNG (Aneziris et al., 2021). Sub-task 1.15 (Review all bunkering procedures and carry out the ship to ship LNG bunker safety checklist with LNG bunker vessel) has the second-highest HEP (3.38E-01). Information exchange is the main reason for high HEP. This stage is critical to avoiding accidents during the fuel transfer operation between two vessels unfamiliar with one another from a technical and specific aspect. The LNG bunkering vessel and the LNG-fuelled ship exchange information and achieve agreements on safety-related concerns during the bunker transfer planning stage, which is a critical component of LNG bunkering. Due to commercial pressures in the maritime industry, fuel operations are frequently requested to be completed immediately, and checklists developed for ship officers under the ISM Code are commonly perceived as paperwork or extra effort. It is critical to review the properly signed checklists at specified intervals and periods. As a result, it is vital to rigorously apply the IAPH-developed standard ship to ship bunker checklist throughout operations (IAPH, 2019).

In the pre-bunkering activities, sub-task 2.8 (Carry out adequate supervision of the bunker operation by responsible officers is in place, both on the ship and at the LNG bunker vessel) has the highest HEP, which is 4.02E-01. The main reason for that failure could be a lack of proper training and experience for the person in charge. The appropriate level of training and expertise of all individuals engaging in LNG bunkering operations is critical. This will aid in avoiding the possibility of complacency and control work and rest hours to minimise fatigue during the workday. In addition, the crew should be thoroughly knowledgeable about the equipment, systems, and onboard procedures. In addition, providing specific operational familiarisation training on each ship that carries out LNG bunker operations can contribute to the safe execution of this task. The sub-task 2.39 (Carry out information exchange about pre-cooling, inerting, cooling down, vapour management, rates of transfer during the initial, bulk, topping stage, and filling sequence) has the second highest HEP value with 2.64E-01. Miscommunications of essential operation phases are a significant cause of failure and an increased probability of human error. In addition, inadequate experience and risk acceptance may cause errors in performing this task. Preparation for this task should include exchanging information between experienced officers and compliance with national and international rules. LNG fuel has certain features related to its chemical composition; for example, the temperature is a critical factor, as heated LNG evaporates rapidly. On the other hand, the initial loading rate, topping rate, and vapour management are also critical considerations. Before starting the operation, discussing some critical stages, exchanging information, and agreeing on how to carry it out is necessary. Pre-cooling, inerting, cooling down, vapour management, transfer rates during the initial, bulk, topping stage, and filling sequence are the critical stages of the bunkering operation. Both ships' LNG transfer systems should be pre-cooled to provide a homogeneous temperature distribution throughout the system, performed using nitrogen or LNG. This task involves risks such as cryogenic hazards, oxygen introduction into restricted spaces, and boil-off gas (Podimatas, 2020). Sub-task 2.14 (Maintain an active deck watch on the ship. Maintain an effective LNG bunker watch, both on board and on board the LNG bunker) has the third-highest HEP (2.33E-01) in the pre-bunkering activities. While a compelling deck watch eliminates the hazards that may arise during the STS LNG operation, on the other hand, with a persuasive LNG bunker watch, emergencies such as possible overflow and leakage can be detected beforehand. Due to commercial considerations and the absence of adequate time on ships, numerous operations (provision supply, water/oil supply, and crew change) are conducted simultaneously during bunkering operations. It is recommended not to carry out any simultaneous operation during the LNG fuel operation, and if necessary, necessary controls and risk assessments should be made. The critical element is that the LNG bunkering watchman should have no other duties than the operation. Before the bunkering operation, authorised personnel should identify roles and responsibilities, and deck watch and bunker watch schedules should be designed to ensure continuous monitoring of all processes. A constant deck watch should be kept for mooring lines, dropped anchors, fenders, and simultaneous operations. As mentioned in this description, this area is to be continuously supervised by a watchman entirely independent of the other deck watches and is planned to ensure the operation's safety. The LNG bunker watch is constantly cautious about LNG hoses, LNG manifolds, and LNG bunker controls (IAPH, 2019).

According to Figure 2, sub-task 3.1 (Agreed on starting temperatures, starting pressures, and available tank capacity) has the highest HEP (3.54E-01), whereas sub-task 3.3 (Agreed maximums and minimums (pressures during bunkering, pressures in the LNG bunker tanks, temperatures of the LNG, filling limit of the LNG bunker tanks)) has the second-highest HEP (1.47E-01) during the bunkering operation. Thus, these two tasks are closely linked and critical during the bunkering operation. Inadequate operations management by the supervisor, task planning, and briefing among the parties may lead to failure to exchange necessary information. Knowing the maximum and minimum pressure values is essential to reach normal operational parameters after the initial loading is started safely and everything is checked according to the checklist. On the other hand, continuous monitoring of these parameters is a reliable way to prevent potential overflow or leakage. The LNG loading rate should be reduced when approaching the topping-off level, and the LNG bunker vessel should be notified regarding the pre-agreement. Before initiating fuel operation, it is critical to verify that the operation proceeds safely by minimising manifold pressure and loading rate. Determining the initial temperature is also critical in this process to ensure a homogeneous temperature. Therefore, all parties should exchange information regarding the initial temperature, initial pressure, and tank capacity. Problems caused during this process may result in LNG leakage, overflow, or rapid evaporation at the beginning of the bunker transfer.

Sub-task 4.4 (Inert the bunker transfer pipeline and hose with nitrogen prior to the disconnection), in the phase after bunkering activities, has the highest HEP value (3,40E-01). In order to properly disconnect the bunker transfer pipeline and hose, nitrogen should be supplied into the system to prevent the explosive mixture. There could be a significant amount of cold vapour present, which could be inhaled. Extreme precautions should be maintained when disconnecting because frostbite can be caused by cold vapours or pipelines, among other things. As a result, various factors may contribute to the failure to complete this task successfully. For example, inadequate training and experience on the part of the person in charge may result in specific errors in executing this task. In the same way, fatigue and negligence could be identified as contributing factors. Sub-task 4.3 (Check All pressure release valves and vents to prevent potential over pressurisation) has the second-highest HEP (1.44E-01) during post-bunkering activities. Once bunkering transfer is complete, bunker pipelines and hoses should be drained and stripped to avoid the possibility of over-pressurization. The pressure in the pipeline and vents can spread vapour around during the hose disconnection, which can be inhaled and harm human health and ship equipment. However, negligence, inadequate personnel, and a lack of sleep could result in errors and even catastrophes when carrying out this task. Therefore, performing this operation by experienced personnel will prevent possible mistakes.

4. Conclusion

LNG is emerging as the preferred future fuel in many industries due to its higher efficiencies and fewer environmental concerns. There has been a significant rise in the transportation, storage, and use of LNG as a fuel across the globe. Nevertheless, the fact that LNG is a cryogenic fluid with vapour dispersion properties and is hence highly combustible brings numerous health and safety challenges. During LNG ship to ship bunkering, the potential accident may cause catastrophic results such as severe fatality, or total loss of vessel and cargo. In this context, human reliability analysis is paramount to enhancing safety. This paper proposes a conceptual framework for systematically assessing human reliability for STS LNG bunkering operational stages under an extended D-S evidence fusion HEART approach. The novelty of the article is that it is considered the first research for the HRA operation on the topic of the ship to ship LNG bunkering. In addition, some limitations are overcome with an extended D-S evidence fusion HEART methodology. Although HEART is a practical method for human reliability analysis, it may face the problem of combining multiple experts, such as selecting multiple EPCs and assigning different weights to EPCs. The D-S evidence fusion theory is used to overcome this situation, which considers vague, imprecise, and incomplete information. The D-S evidence fusion theory accepts the information obtained from each expert as a piece of evidence and provides the process of combining the evidence. This method provides HEART practitioners with a robust solution for determining APOA.

In view of the findings, human reliability is found to be 5.98E-01, which is reasonable but not at the desired level for the process. In this case, it can be said that human performance is based on limited planning, and a more or less known procedure is followed. On the other hand, distinctive features of the tasks performed (such as time constraints or incomplete understanding of the task) may impact the successful completion of the task. In this context, the operator can be guided by his habits and experience. Careless characteristics of the situation ascertain the choice of the following action due to human-oriented errors. Therefore, human reliability should be increased. Potential root causes of the human errors in the operation are ascertained, and the highest HEP values are discussed in the paper. Besides its robust theoretical background, the paper's findings provide a ground-breaking way to improve safety in LNG STS bunkering operations, minimise the risk to life and property, and avoid accidents such as overflowing, leakage, fire, and explosions. Future research will handle data derivation and uncertainty in probabilistic reliability assessment (PRA) under a simulation environment.

Nomenclature

$\overline{\mathrm{APOA}}$	Integrated APOA
APOA	Assess the Proportion of Effect
BPA	Basic Probability Assignment
CREAM	Cognitive Reliability and Error Analysis Method
CO2	Carbon Dioxide
Crd	Credibility
DNV-GL	Det Norske Veritas – Germanischer Lloyd
DPA	Designated Person Ashore
D–S	Dempster-Shafer
EPC	Error Producing Condition
FOD	Frame of Discernment
GEP	Generic Error Probability

GHG	Greenhouse Gas
GTT	Generic Task Type
HEART	Human Error Assessment and Reduction Technique
HEP	Human Error Probability
HFACS	Human Factors Analysis and Classification System
HRA	Human Reliability Analysis
HTA	Hierarchical Task Analysis
IAPH	International Association of Ports and Harbours
IGF Code	International Code of Safety for Ships Operating Using on Gases or Other Low-Flashpoint Fuels
IGU	International Gas Union
IMO	International Maritime Organization
ISM	International Safety Management
k	Conflict Coefficient
LNG	Liquid Natural Gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MEPC	Marine Environment Protection Committee
NOx	Nitrogen oxides
P&I	Protection and Indemnity Insurance
PM	Particular Matter
PRA	Probabilistic Reliability Assessment
SLIM	Success Likelihood Index Method
SMS	Safety Management System
SO_2	Sulphur Oxide
STCW	International Convention on Standards of Training, Certification and Watchkeeping for Seafarers
STS	Ship to Ship
Θ	Frame of Discernment

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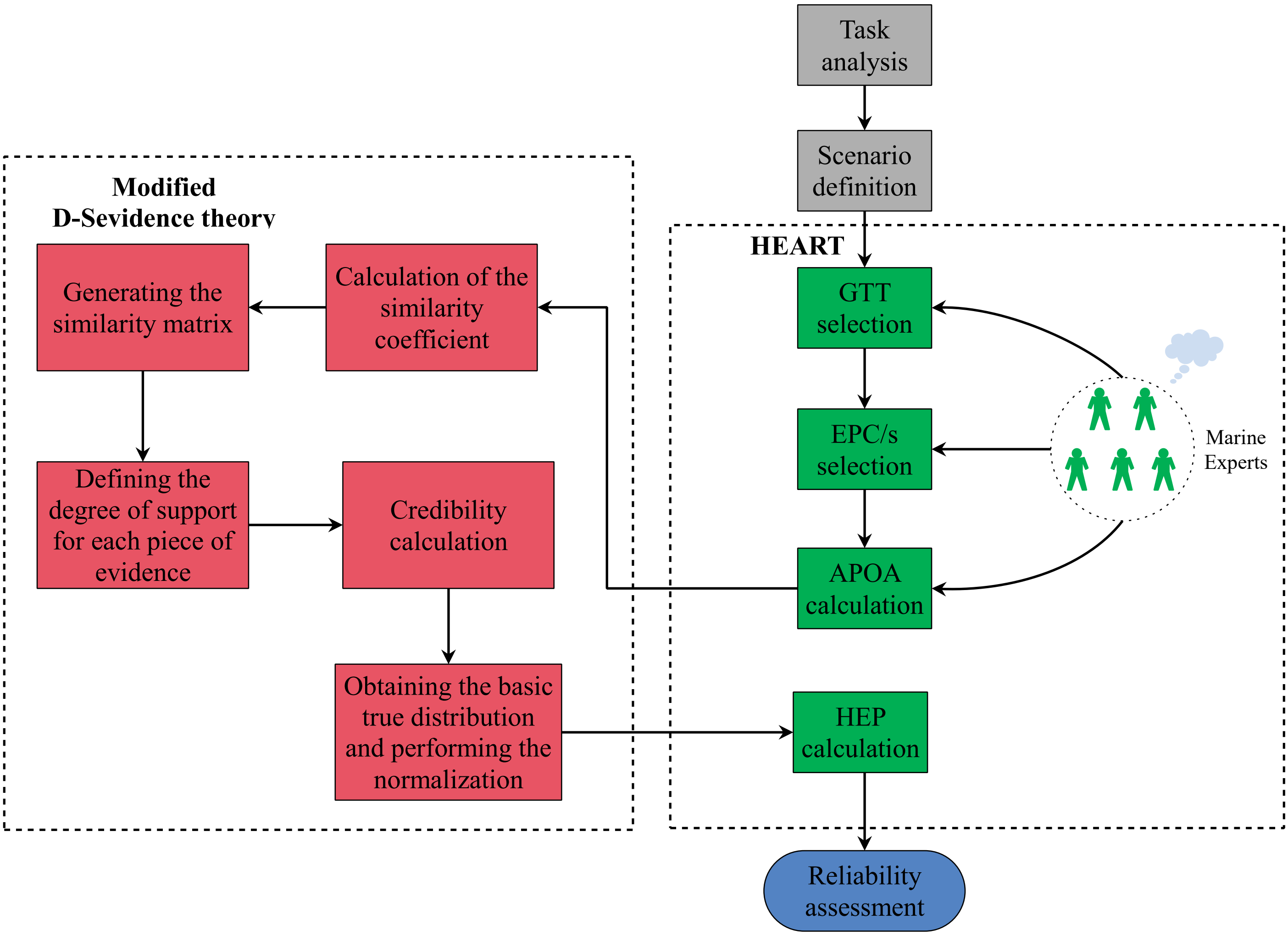
HIGHLIGHTS

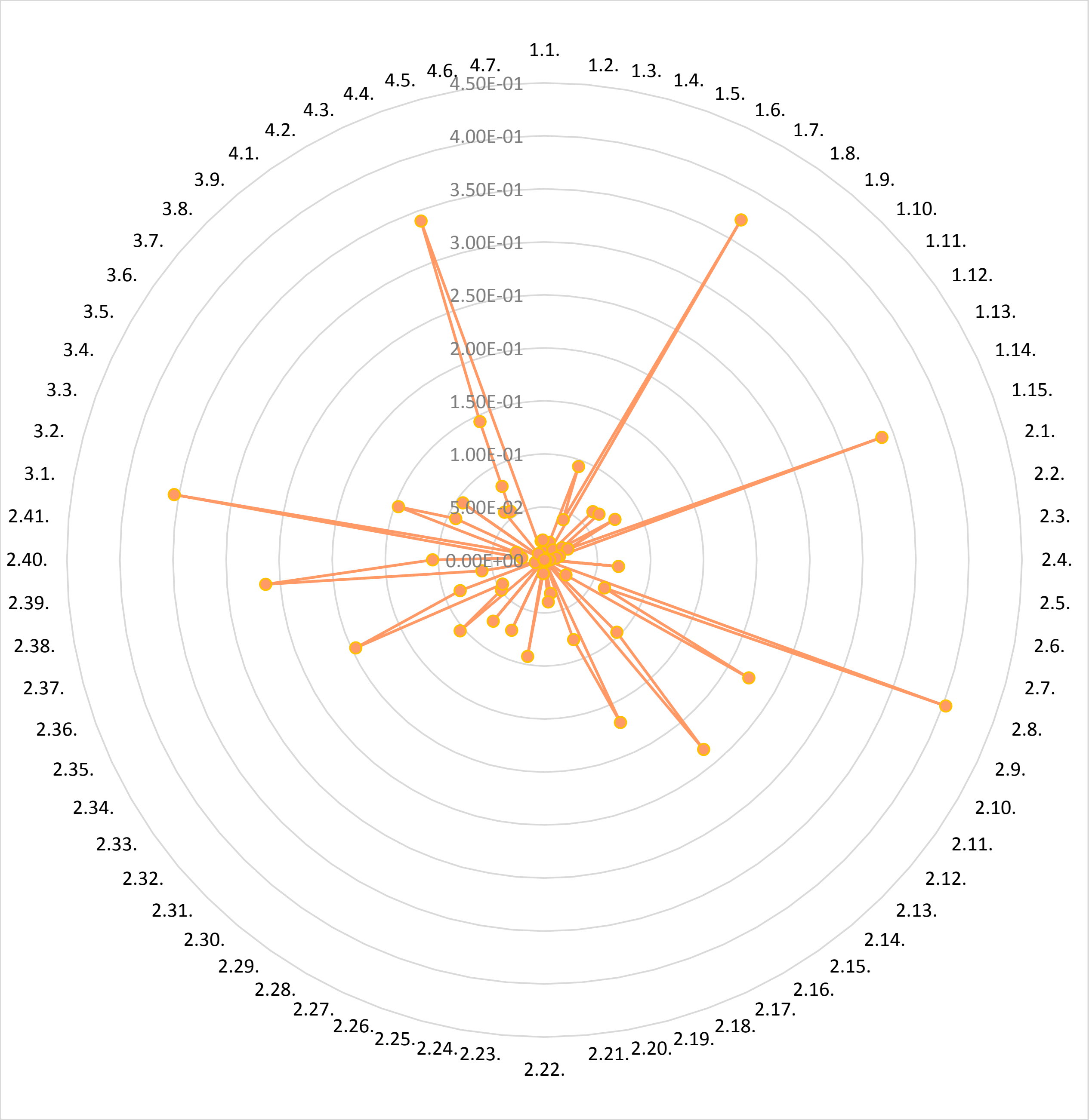
A human reliability analysis for ship to ship LNG bunkering process under D-S evidence fusion HEART approach.

- Enhancing safety and minimizing human error for ship to ship LNG bunkering process.
- Experts' assessments are fused with the help of modified D-S evidence theory.
- Human reliability analysis for ship to ship LNG bunkering process.

< Fig. 1. Flow diagram of proposed approach >



< Fig. 2. HEP distribution for sub-tasks >



< Revised Table 1. Notation in line of the rules>

System description	System sub-task dependency	Notation for task HEP
Parallel system	High dependency	$HEP_{Task} = Min\{HEP_{Sub-task\ i}\}$
	Low or no dependency	$HEP_{Task} = \prod(HEP_{Sub-task\ i})$
Serial system	High dependency	$HEP_{Task} = Max\{HEP_{Sub-task\ i}\}$
	Low or no dependency	$HEP_{Task} = \sum(HEP_{Sub-task\ i})$

< Revised Table 2. HTA of STS LNG bunkering operation>

STS LNG bunkering operation
1. Planning Stage
1.1 Notify and Approved from port authorities, Flag Administration for LNG transfer operations with specific location and time
1.2 Observe all applicable local and national regulations and guidelines (ignition source etc.)
1.3 Agree on the date, time, geographical location (condition of the jetty/anchorage/traffic), bunker quantities, and quality between the vessels
1.4 Agreed on the weather and sea criteria, and limits for aborting the operation
1.5 Establish (set out) the safety zone and security zone with port authority. Designate and agree on restricted areas
1.6 Conduct the appropriate training, emergency exercises, drills, and instruct on the particular LNG bunker equipment and procedures to all crew involved in the LNG bunker operation. Clearly define their duties and responsibilities prior to bunkering
1.7 Communicate and agree on contingency plan and emergency response plan to all parties involved in the bunkering operation including the planned emergency response team
1.8 Confirm The LNG BMPs and operations manuals of both vessels and exchange the necessary approval certificates
1.9 Agree on the compatibility of the two ships performing STS Bunkering, including mooring, fendering, and bunker transfer equipment
1.10 Cary out to verify the condition of firefighting equipments, lights, PPE, spill equipment, radio communication equipment, Emergency Shut Down System, mooring equipment, fenders, if available, and transfer equipment with equipment certificates
1.11 Test all alarms and safety devices following the company procedures and local requirements
1.12 Agreed on the procedures for bunkering, cooling down and purging operations by LNG Bunker vessel
1.13 Inspect the own bunker transfer equipment and pipelines visually
1.14 Agree on the system and method of electrical insulation with the LNG Bunker vessel
1.15 Review all bunkering procedures and carry out the ship-to-ship LNG bunker safety checklist with LNG bunker vessel
2. Pre-Bunkering Activities
2.1 Notify Competent authorities, Bunker Ship the start of LNG bunker operations as per local regulations
2.2 Check and agree on the weather and sea criteria, and limits for aborting the operation
2.3 Provide securely mooring between own ship and LNG bunker vessel according to the regulations with regards to mooring arrangements (sufficient rendering and mooring etc.)
2.4 Arrange a safe means of access between the own ship and the LNG bunker vessel
2.5 Prepare all mandatory firefighting equipment ready for immediate use and exchange the smoking regulations and other fire prevention measures
2.6 Illuminate sufficiently the bunker operation area
2.7 Confirm that own ship and LNG bunker vessel are able to move under their own power in a safe and non-obstructed direction
2.8 Carry out adequate supervision of the bunker operation by responsible officers is in place, both on the own ship and at the LNG bunker vessel
2.9 Establish, test, and agree on an effective means of communication (main and emergency) and between the responsible operators and supervisors at the own ship and LNG bunker vessel. Agree on the communication language
2.10 Agree, test and explain to all relevant personnel the emergency stop signal and shutdown procedures
2.11 Make sure that emergency procedures and plans and contact numbers are known to those in charge
2.12 Create predefined restricted area. Appropriate signs mark this area. Clear the restricted area from other ships, unauthorized persons, objects and ignition sources
2.13 Agree on safety procedures and mitigation measures to prevent falling objects and comply with them by all parties involved
2.14 Maintain an active deck watch on the ship. Maintain an effective LNG bunker watch, both on board and

on board the LNG bunker

2.15 Close external doors, portholes and accommodation ventilation inlets according to the operating manual

2.16 Test the gas detection equipment operationally and determine that it is in good working order

2.17 Material Safety Data Sheets (MSDS) for delivered LNG fuel must be on board

2.18 Enforce regulations regarding ignition sources

2.19 Ensure that appropriate and adequate protective clothing and equipment are immediately available, and that personnel involved in connecting and disconnecting bunker hoses and personnel in the immediate vicinity of these operations use adequate and appropriate protective clothing and equipment

2.20 Install a [powered] emergency release coupling ([P]ERC) and have it ready for immediate use

2.21 Test the water spray system and have it ready for immediate use

2.22 Check that Spill containment arrangements have appropriate material and volume are in place and empty

2.23 Verify that hull and deck protection against low temperature is present

2.24 Verify that bunker pumps and compressors are in good working order

2.25 Verify that all control valves are in good condition and in good working order

2.26 Verify that the bunker system gauges, high-level alarms, and high-pressure alarms are operational, correctly set, and in good working order

2.27 Ensure the ship's bunker tanks are always protected against accidental overflow, the tank contents are constantly monitored and alarms are set correctly

2.28 Check, test and verify that all safety and control devices in LNG installations are in good working order

2.29 Verify that pressure control equipment and boil-off or re-liquefaction equipment are in good working order

2.30 Connect and support the vapour connections properly

2.31 Verify that ESDs, automatic valves or similar devices have been tested, in good working order, and ready for use, both on board and on board the LNG bunker. Agreed on the closing rates of the ESDs

2.32 Check out the initial LNG bunker line up. Close unused connections, blank and bolt completely

2.33 Check that LNG bunker hoses, fixed pipelines, and manifolds are in good condition, properly equipped, supported, properly connected, leak-tested, and certified for LNG transfer

2.34 Provide the LNG bunker connection between the ship and the LNG bunker ship with dry disconnection couplings

2.35 Ensure the LNG bunker connection between the own ship and the LNG bunker ship with adequate electrical isolation means in place

2.36 Dry breakaway couplings on LNG bunker connections are in place, visually check that they are working and are in good working order

2.37 Locate the ship’s emergency fire control plans externally

2.38 Provide an International Shore Connection

2.39 Carry out information exchange about pre-cooling, inerting, cooling down, vapour management, rates of transfer during the initial, bulk, topping stage, and filling sequence

2.40 Carry out initial pre-cooling of the LNG transfer systems of both vessels that can be completed either with the use of nitrogen or with LNG. Aware of the risks of cryogenic hazards, introducing oxygen in confined spaces, and boil-off-gas (if inerting with LNG) during this activity

2.41 Inform the component authorities that bunker transfer operations are commencing and have been requested to inform other vessels in the vicinity

3. During Bunkering Activities

3.1. Agreed on starting temperatures, starting pressures and available tank capacity

3.2 Agreed on quantity to be transferred, starting pressure at the manifold, starting rate, max. transfer rate, topping up rate, max. pressure at manifold

3.3 Agreed maximums and minimums (pressures during bunkering, pressures in the LNG bunker tanks, temperatures of the LNG, filling limit of the LNG bunker tanks)

3.4 Start at the agreed rates (temperatures, pressures and tank capacity)

3.5 Monitor bunker transfer quantities, temperatures, pressures and tank capacity

3.6 Manage the vented and boil-off gas in accordance with the agreed plan

3.7 Monitor the weather condition and any unexpected deterioration

3.8 Adjust mooring lines and bunker hoses and arms as necessary

3.9 Test the communication equipment/methods periodically

4. After Bunkering Activities

4.1. Purge LNG bunker hoses, fixed pipelines, and manifolds and maintain them ready for disconnection

4.2 Close remote and manually controlled valves and keep them ready for disconnection

4.3 Check All pressure release valves and vents to prevent potential over pressurisation

4.4 Inert the bunker transfer pipeline and hose with nitrogen prior to the disconnection

4.5 Deactivate the restricted area after disconnection

4.6 Notify competent authorities and terminal that LNG bunker operations have been completed and have been requested to inform other vessels in the vicinity

4.7 Report near misses and incidents to competent authorities if available

< Revised Table 3. Selected GTT and EPC/s for ship to ship LNG bunkering operation >

Sub-task	GTT	Selected EPC/s
1.		
1.1	F	EPC 2, 10, 15, 16
1.2	G	EPC 16, 32
1.3	F	EPC 10, 16
1.4	F	EPC 10, 14, 16
1.5	E	EPC 12, 15
1.6	E	EPC 10, 15, 22
1.7	D	EPC 10, 16
1.8	G	EPC 10, 16
1.9	E	EPC 10, 15, 16
1.10	E	EPC 2, 17, 23
1.11	E	EPC 14, 23
1.12	F	EPC 10, 15
1.13	E	EPC 2, 23
1.14	F	EPC 10, 12
1.15	D	EPC 15, 17, 18
2.		
2.1	F	EPC 2, 10, 15, 16
2.2	F	EPC 10, 14, 16
2.3	G	EPC 13, 15, 17
2.4	F	EPC 22, 23
2.5	E	EPC 12, 25
2.6	H	EPC 23
2.7	G	EPC 15, 17, 23
2.8	D	EPC 2, 15, 17
2.9	E	EPC 3, 22, 23
2.10	E	EPC 1, 10, 15
2.11	F	EPC 1, 15, 16
2.12	H	EPC 5, 12
2.13	E	EPC 12, 15
2.14	E	EPC 2, 17, 21, 25
2.15	G	EPC 17, 23
2.16	G	EPC 15, 19, 23
2.17	E	EPC 6, 16
2.18	E	EPC 15, 16
2.19	G	EPC 15, 20
2.20	E	EPC 23
2.21	E	EPC 2, 23
2.22	G	EPC 8, 17
2.23	F	EPC 12, 15
2.24	E	EPC 11, 15
2.25	G	EPC 15, 25, 32
2.26	G	EPC 15, 25, 32
2.27	E	EPC 15, 17, 20
2.28	G	EPC 15, 17, 23
2.29	G	EPC 15, 17, 23
2.30	D	EPC 15, 17, 23
2.31	H	EPC 12, 15, 23
2.32	E	EPC 12, 14, 23
2.33	E	EPC 12, 15, 23
2.34	E	EPC 15, 23
2.35	D	EPC 15, 23
2.36	E	EPC 12, 15, 17
2.37	F	EPC 17
2.38	E	EPC 17

2.39	D	EPC 10, 12, 15, 16
2.40	E	EPC 10, 12, 15
2.41	F	EPC 2, 10, 15
3.		
3.1	D	EPC 10, 15, 17
3.2	F	EPC 2, 10, 15
3.3	E	EPC 10, 12, 15
3.4	E	EPC 14, 15, 17
3.5	G	EPC 12, 15, 23, 28
3.6	E	EPC 1, 12, 15, 23
3.7	G	EPC 12, 15, 28
3.8	F	EPC 10, 15, 28
3.9	E	EPC 3, 22, 23
4.		
4.1	E	EPC 12, 17, 23
4.2	E	EPC 14
4.3	D	EPC 23
4.4	E	EPC 1
4.5	H	EPC 14, 16
4.6	F	EPC 2, 10, 15, 16
4.7	F	EPC 12, 13

< Revised Table 4. Conflict coefficient between marine experts for subtask 1.1>

Pairwise of experts	Conflict coefficient
$k(e_1, e_2)$	0.67
$k(e_1, e_3)$	0.66
$k(e_1, e_4)$	0.63
$k(e_1, e_5)$	0.67
$k(e_2, e_3)$	0.77
$k(e_2, e_4)$	0.63
$k(e_2, e_5)$	0.62
$k(e_3, e_4)$	0.73
$k(e_3, e_5)$	0.77
$k(e_4, e_5)$	0.63

< Revised Table 5. HEP and $\overline{APOA}$ calculation results of STS LNG bunkering operation>

Sub-task	EPC/s	$\overline{APOA}$	HEP value
1.1	EPC2	0.016	1.64E-02
	EPC10	0.081	
	EPC15	0.642	
	EPC16	0.262	
1.2	EPC16	0.090	5.58E-04
	EPC32	0.910	
1.3	EPC10	0.046	1.05E-02
	EPC16	0.954	
1.4	EPC10	0.313	1.74E-02
	EPC14	0.467	
	EPC16	0.219	
1.5	EPC12	0.341	9.38E-02
	EPC15	0.659	
1.6	EPC10	0.006	4.18E-02
	EPC15	0.090	
	EPC22	0.904	
1.7	EPC10	0.106	3.70E-01
	EPC16	0.894	
1.8	EPC10	0.307	2.27E-03
	EPC16	0.693	
1.9	EPC10	0.036	1.23E-02
	EPC15	0.569	
	EPC16	0.395	
1.10	EPC2	0.022	6.44E-02
	EPC17	0.552	
	EPC23	0.426	
1.11	EPC14	0.545	6.71E-02
	EPC23	0.455	
1.12	EPC10	0.659	2.00E-02
	EPC15	0.341	
1.13	EPC2	0.154	7.67E-02
	EPC23	0.846	
1.14	EPC10	0.463	2.42E-02
	EPC12	0.537	
1.15	EPC15	0.143	3.38E-01
	EPC17	0.734	
	EPC18	0.123	
2.1	EPC 2	0.004	1.45E-02
	EPC10	0.071	
	EPC15	0.246	
	EPC16	0.678	
2.2	EPC10	0.087	1.13E-02
	EPC14	0.565	
	EPC16	0.348	
2.3	EPC13	0.371	1.13E-03
	EPC15	0.168	
	EPC17	0.461	
2.4	EPC22	0.074	4.94E-03
	EPC23	0.926	
2.5	EPC12	0.611	6.99E-02
	EPC25	0.389	
2.6	EPC23	1.000	3.20E-05
2.7	EPC15	0.036	7.29E-04
	EPC17	0.048	
	EPC23	0.916	
2.8	EPC2	0.082	4.02E-01
	EPC15	0.730	

	EPC17	0.188	
2.9	EPC3	0.086	6.24E-02
	EPC22	0.651	
	EPC23	0.263	
2.10	EPC1	0.063	2.22E-01
	EPC10	0.340	
	EPC15	0.597	
2.11	EPC1	0.087	2.47E-02
	EPC15	0.695	
	EPC16	0.217	
2.12	EPC5	0.214	1.68E-04
	EPC12	0.786	
2.13	EPC12	0.388	9.63E-02
	EPC15	0.612	
2.14	EPC2	0.525	2.33E-01
	EPC17	0.295	
	EPC21	0.159	
	EPC25	0.021	
2.15	EPC17	0.693	1.13E-03
	EPC23	0.307	
2.16	EPC15	0.700	1.26E-03
	EPC19	0.125	
	EPC23	0.175	
2.17	EPC6	0.413	1.69E-01
	EPC16	0.587	
2.18	EPC15	0.537	7.99E-02
	EPC16	0.463	
2.19	EPC15	0.908	1.23E-03
	EPC20	0.092	
2.20	EPC23	1.000	3.20E-02
2.21	EPC2	0.026	3.98E-02
	EPC23	0.974	
2.22	EPC8	0.380	2.60E-03
	EPC17	0.620	
2.23	EPC12	0.241	1.30E-02
	EPC15	0.759	
2.24	EPC11	0.191	9.23E-02
	EPC15	0.809	
2.25	EPC15	0.641	1.07E-03
	EPC25	0.293	
	EPC32	0.066	
2.26	EPC15	0.910	1.15E-03
	EPC25	0.034	
	EPC32	0.056	
2.27	EPC15	0.389	7.31E-02
	EPC17	0.262	
	EPC20	0.349	
2.28	EPC15	0.549	1.42E-03
	EPC17	0.262	
	EPC23	0.189	
2.29	EPC15	0.702	1.48E-03
	EPC17	0.248	
	EPC23	0.049	
2.30	EPC15	0.301	7.54E-02
	EPC17	0.631	
	EPC23	0.068	
2.31	EPC12	0.065	6.50E-05
	EPC15	0.683	
	EPC23	0.253	
2.32	EPC12	0.295	1.04E-01

	EPC14	0.473	
	EPC23	0.232	
2.33	EPC12	0.023	4.97E-02
	EPC15	0.341	
	EPC23	0.636	
2.34	EPC15	0.307	4.57E-02
	EPC23	0.693	
2.35	EPC15	0.253	1.96E-01
	EPC23	0.747	
2.36	EPC12	0.035	8.47E-02
	EPC15	0.393	
	EPC17	0.572	
2.37	EPC17	1.000	9.00E-03
2.38	EPC17	1.000	6.00E-02
2.39	EPC10	0.076	2.64E-01
	EPC12	0.226	
	EPC15	0.152	
	EPC16	0.547	
2.40	EPC10	0.054	1.05E-01
	EPC12	0.264	
	EPC15	0.682	
2.41	EPC2	0.008	2.14E-02
	EPC10	0.615	
	EPC15	0.377	
3.1	EPC 10	0.064	3.54E-01
	EPC 15	0.884	
	EPC 17	0.052	
3.2	EPC 2	0.067	2.76E-02
	EPC 10	0.336	
	EPC 15	0.597	
3.3	EPC 10	0.197	1.47E-01
	EPC 12	0.336	
	EPC 15	0.466	
3.4	EPC 14	0.198	9.23E-02
	EPC 15	0.698	
	EPC 17	0.104	
3.5	EPC 12	0.069	1.03E-03
	EPC 15	0.269	
	EPC 23	0.549	
	EPC 28	0.113	
3.6	EPC 1	0.022	9.40E-02
	EPC 12	0.195	
	EPC 15	0.392	
	EPC 23	0.391	
3.7	EPC 12	0.058	7.83E-04
	EPC 15	0.129	
	EPC 28	0.813	
3.8	EPC 10	0.067	8.37E-03
	EPC 15	0.378	
	EPC 28	0.556	
3.9	EPC 3	0.098	5.86E-02
	EPC 22	0.030	
	EPC 23	0.873	
4.1	EPC12	0.154	5.58E-02
	EPC17	0.182	
	EPC23	0.664	
4.2	EPC14	1.000	8.00E-02
3.3	EPC23	1.000	1.44E-01
4.4	EPC1	1.000	3.40E-01
4.5	EPC14	0.373	9.55E-05

	EPC16	0.627	
4.6	EPC2	0.001	1.80E-02
	EPC10	0.177	
	EPC15	0.479	
	EPC16	0.344	
4.7	EPC12	0.468	1.87E-02
	EPC13	0.532	

Table-6

< Revised Table 6. HEP calculation steps for subtask 1.1>

Steps			Steps	
e_1	EPC2	0.1	sim(e_3, e_4)	0.751
	EPC10	0	sim(e_3, e_5)	0.640
	EPC15	0.5	sim(e_4, e_5)	0.974
	EPC16	0.4	sup(e_1)	3,478
e_2	EPC2	0	sup(e_2)	3.440
	EPC10	0.3	sup(e_3)	2.931
	EPC15	0.5	sup(e_4)	3.625
	EPC16	0.2	sup(e_5)	3.440
e_3	EPC2	0.3	Crd(e_1)	0.206
	EPC10	0	Crd(e_2)	0.203
	EPC15	0.3	Crd(e_3)	0.173
	EPC16	0.4	Crd(e_4)	0.214
e_4	EPC2	0	Crd(e_5)	0.203
	EPC10	0.2	e_c(EPC2)	0.073
	EPC15	0.5	e_c(EPC10)	0.165
	EPC16	0.3	e_c(EPC15)	0.465
e_5	EPC2	0	e_c(EPC16)	0.297
	EPC10	0.3	$\overline{APOA}_2$	0.016
	EPC15	0.5	$\overline{APOA}_{10}$	0.081
	EPC16	0.2	$\overline{APOA}_{15}$	0.642
sim(e_1, e_2)	0.826		$\overline{APOA}_{16}$	0.262
sim(e_1, e_3)	0.900		EPC_2 effect	11
sim(e_1, e_4)	0.926		EPC_{10} effect	5.5
sim(e_1, e_5)	0.826		EPC_{15} effect	3
sim(e_2, e_3)	0.640		EPC_{16} effect	3
sim(e_2, e_4)	0.974		GEP value	0.003
sim(e_2, e_5)	1.000		HEP	1.64E-02

Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Author statement

Esma Uflaz: Conceptualization, Methodology, Reviewing, Editing
Sukru Ilke Sezer: Visualization, Investigation, Writing, Methodology, Data curation
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