

Prediction of Human Error in Chemical Tanker Ship's Tank Heating Process to Enhance Operational Safety

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Abstract

Depending on the nature of the cargo, specific temperatures must be maintained throughout the safe carrying and loading/unloading of chemical tankers. In this regard, tank heating systems are essential for maintaining the proper temperature range for chemical cargoes, particularly those transported at viscous or near-freezing temperatures. The operational process presents safety challenges because of the nature of the task that the ship crew must perform. Since human error is increasingly a major contributor to marine mishaps, this paper conducts a systematic human error prediction to ensure safe tank heating operations under various conditions. However, improper use of these systems can cause problems such as fire and explosion risk due to overheating, toxic gas formation, cargo deterioration, and equipment damage. This study examines operational practices and risks related to using tank heating systems in chemical tankers; evaluations are made in terms of energy efficiency, cargo safety, and environmental impacts. The paper discusses the fuzzy approach's Success Likelihood Index Method (SLIM) to achieve this. The fuzzy approach in the suggested method can assist experts' judgment in decision-making, and the SLIM offers a thorough human error prediction tool. "Perform the temperature increase gradually and prevent sudden temperature increases" is identified as a critical task with the highest human error probability (HEP: 5.28E-02) during chemical tanker tank heating operations.

Keywords Maritime safety; Human error; Success likelihood index method; Tank heating; Tanker ship

1 Introduction

Maritime transport is highly valued for its economic efficiency, safety, and environmental sustainability in cargo transportation, with approximately 90% of global trade volume being moved by sea (UNCTAD, 2023). Maritime accidents can lead to substantial financial losses, fatalities, and marine pollution, resulting in a global consensus on the necessity of maritime safety (Sezer et al., 2023). Despite a significant 70% reduction in yearly shipping losses over

the past decade, the dangers associated with marine accidents persist (Allianz Global Corporate & Specialty). According to the European Maritime Safety Agency (EMSA) Annual Overview of Marine Casualties and Incidents 2023, which analyzes data reported by European Union (EU) Member States from 2014 to 2022, 59.1% of incidents were attributable to human activities, while 50.1% of contributory factors were associated with human conduct. The human element was linked to 80.7% of the examined marine casualties and events when considering human actions and behavioral elements collectively (EMSA, 2023). These percentages highlight the substantial impact of human factors in maritime incidents, emphasizing the need for accurate human error assessment and mitigation strategies.

The International Maritime Organization (IMO) has established proactive regulatory frameworks to regulate maritime operations and ensure maritime safety. The list comprises the International Convention for the Safety of Life at Sea (SOLAS), the International Convention on Standards of Training, Certification, and Watchkeeping for Seafarers (STCW), the International Convention for the Prevention of Pollution from Ships, 1973 as modified by the Protocol of 1978 (MARPOL 73/78), and the Convention on the International Regulations for Preventing Collisions at Sea (COLREG). The SOLAS Convention establishes

Article Highlights

- The human error in the chemical tanker ship's tank heating operation process is determined.
- The fuzzy approach copes with the vagueness and subjectivity in the decision-making process, while the success likelihood index method systematically predicts the human error probability.
- The operational safety and performance reliability are enhanced for the tank heating operation of chemical tankers.

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baseline requirements for the safe operation of vessels and enhances maritime safety through regulatory rules. On the other hand, there are hazards arising from the characteristics of the cargoes carried on chemical tanker ships as well as hazards arising from the complex operations carried out. For this reason, additional guides and codes such as International Safety Guide for Oil Tankers and Terminals (ISGOTT), Tanker Management and Self Assessment (TMSA), International Code for the Construction and Equipment of Ships carrying Dangerous Chemicals in Bulk (IBC), and Tanker Safety Guide are taken into consideration in order to increase the safety level in chemical tanker ships (Sezer et al., 2023). Notwithstanding the establishment of safety frameworks that mitigate maritime accidents, persistent compliance issues, technological progress, volatile operating environments, and inadequate laws nonetheless exacerbate incidents attributable to human error (Adumene et al., 2022). Human errors in marine operations can result in significant repercussions for property, the environment, and human life, impacting navigation, cargo handling, and ship-to-ship transfers (Akyuz and Celik, 2018; Sezer et al., 2022). Human reliability analysis (HRA) is a methodology employed in diverse human-machine systems to examine the causes and consequences of human errors (Arici et al., 2024). Evaluating human performance and mitigating deadly accidents rely on identifying the human error probability (HEP). The Cognitive Reliability and Error Analysis Method (CREAM) (Ahn and Kurt, 2020; Aydin et al., 2021; Zhou et al., 2018), Technique for Human Error Rate Prediction (THERP) (Martins, and Maturana, 2010; Zhang et al., 2020, Ramezani et al., 2020), Human Error Assessment and Reduction Technique (HEART) (Wang et al., 2024; Uflaz et al., 2022; Kandemir et al., 2019), Standardized Plant Analysis Risk Human Reliability Analysis (SPAR-H) (Ahn et al., 2022; Elidolu et al., 2023; Liu et al., 2024), Success Likelihood Index Method (SLIM) (Erdem and Akyuz, 2021; Liu et al., 2022; Tekeli et al., 2024), and Human Factor Analysis and Classification System (HFACS) (Qiao et al., 2020; Tang et al., 2022; Oliveira et al., 2023) are commonly utilized in the assessment of human performance within maritime literature.

In addition, although there are various studies in the literature on chemical tanker ships (Sezer et al., 2023; Elidolu et al., 2022b; Akyuz et al., 2018; Akyuz and Celik, 2016), there is a research gap on tank heating operation. This paper intends to compute the HEP occurring on chemical tankers during the tank heating operation. This research introduces a hybrid methodology that combines fuzzy sets with SLIM to forecast human-related errors in tank heating operations. The rationale for employing SLIM stems from data scarcity, as it relies significantly on expert judgment. The SLIM represents a versatile method for extracting HEPs from context. The SLIM associates' context with human

error. Nonetheless, challenges in assessing the relative significance of Performance Shaping Factors (PSFs) and the absence of assistance in selecting PSFs are drawbacks for SLIM (Spurigin, 2009) unless the expert elicitation procedure is conducted meticulously.

The suggested approach enables SLIM to identify and quantify performance shaping factors (PSFs) that significantly influence human safety performance and to compute human error probability (HEP) values. The fuzzy approach addresses the vagueness and ambiguity inherent in experts' language assessments, hence enhancing consistency in the decision-making process. To accomplish this objective, the paper is structured as follows: This part presents the rationale for the study and an extensive review of the literature about HEP assessments in the maritime industry. Section II provides a comprehensive explanation of the suggested methodology and its integration. Section III presents a practical application of the proposed methodology for tank heating operations. Section IV contains the findings and an extensive discussion. The concluding section delineates the conclusion and the research's significance to maritime transportation.

2 Materials and method

This section presents a hybrid approach that integrates SLIM and fuzzy approaches to drive the probability of human error for a chemical tanker tank heating operation. SLIM is widely recognized for its effectiveness in quantifying human error probabilities (HEP) when empirical data are scarce. Unlike traditional human reliability analysis (HRA) methods such as THERP and HEART, which usually rely on predefined error rates, SLIM allows expert-driven assessment of Performance Shaping Factors (PSFs), making it adaptable to various operational contexts (Erdem and Akyuz, 2021). However, the accuracy of SLIM is largely dependent on expert judgments, which can lead to subjectivity. To address this limitation, the integration of fuzzy logic increases the robustness of the analysis by systematically addressing uncertainty and linguistic ambiguity in expert judgments. This study introduces an adaptation of the Fuzzy SLIM approach specifically tailored for chemical tanker ship tank heating operations. The methodology fills an important gap in human error assessment for maritime safety by focusing on the probability of human error occurring during tank heating operation

2.1 Fuzzy sets

Fuzzy set theory was established to address uncertainties or mistakes in human decision-making, as conventional probability approaches are inadequate for representing such uncertainties (Zadeh, 1965). The approach facilitates the

conversion of subjective assessments and language expressions into quantifiable and numerical data (Khan and Sadiq, 2005). Expert judgment can be articulated in natural language terms such as low, medium, and high, incorporating several different methodologies in the decision-making process (Karmaker et al., 2023; Castiglia and Giardina, 2013). In fuzzy set theory, a fuzzy subset A of X is defined by a membership function $\mu_A(x)$, which links each element x in X to a real integer within the interval $[0, 1]$ (Zadeh, 1965). The function $\mu_A(x)$ indicates the degree of membership of x in the fuzzy set A (Abbasbandy and Hajjari, 2009; Castiglia and Giardina, 2013). Membership functions can assume several shapes, with triangular and trapezoidal forms being the most commonly observed (Barua et al., 2013).

The study employed a trapezoidal membership function. This function can be expressed as the following equation for trapezoidal fuzzy set numbers (a, b, c, d) (Badida et al., 2019; Singh et al., 2022).

$$\mu_A(x) = \begin{cases} \frac{x-a}{b-a}, & a \leq x \leq b \\ 1, & b \leq x \leq c \\ \frac{d-x}{d-c}, & c \leq x \leq d \\ 0, & \text{otherwise} \end{cases} \quad \text{where } a < b < c < d \quad (1)$$

2.2 SLIM

The SLIM signifies the inaugural version of Human Reliability Analysis (HRA) methodologies proposed by Embrey et al. (1984). The main aim is to quantify and predict Human Error Probabilities (HEP) in certain activities, emphasizing Performance Shaping Factors (PSFs) that considerably affect human performance (Islam et al., 2016). Owing to a lack of data, the SLIM mostly depends on the assessments of domain experts for HEP prediction (Park and Lee, 2008). SLIM is successfully used in many sectors (Hameed et al., 2016; Liu et al., 2022; Noman et al., 2023; Zhou et al., 2024; Liao et al., 2025).

The success probability of a task in SLIM is based on the integrated effect of the PSFs. Accordingly, experts weight and rate PSFs using their experience and knowledge. In this way the impact of the PSFs is quantified and the Success Likelihood Index (SLI) is established. The weight assigned to a PSF expresses the relative significance of PSFs, whereas the PSF's rating reflects its effectiveness in performing the task (Tekeli et al., 2024). Ultimately, the HEP value for each task is derived by adjusting the SLI value accordingly (Zhou et al., 2022; Abrishami et al., 2020).

2.3 Integration of methods

This chapter presents a hybrid methodology that inte-

grates fuzzy numbers with SLIM for the quantitative evaluation of human error in the context of tank heating operations on chemical tankers.

Step 1 Task analysis: The initial phase of the suggested methodology is task analysis, wherein the pertinent stages are identified based on the scenario. Task analysis is conducted by hierarchical task analysis (HTA), wherein the primary task comprises subtasks (Shepherd, 2003). In HTA, tasks related to a subject are structured hierarchically by considering the main objective and its associated sub-objectives. The process starts with identifying the primary tasks aligned with the overarching goal of the subject. Subsequently, the sub-objectives required to achieve the main goal are specified, leading to the identification of corresponding sub-tasks. Lastly, the sequence and interrelation of these sub-tasks are determined (Sezer et al., 2023).

Step 2 Scenario definition: This section delineates the operational environment. This may encompass experience, meteorological conditions, time of day, sea state, weariness, tension, work environment, operational disruptions, noise levels, and additional factors. Conditions must be considered as they substantially influence human performance.

Step 3 PSF derivation: In this step, experts identify specific PSFs that notably influence human performance. Factors such as experience, knowledge, education, workload, fatigue, stress, task complexity, communication, and a poor working environment significantly influence human performance.

Step 4 PSF rating: Following the derivation of the PSFs, specialists assign values ranging from 1 to 9 on a linear scale. If a factor substantially influences the failure of crew performance for the pertinent task, maritime professionals designate it a value of 1. Expert evaluations are conducted based on the specific conditions observed during the process. Notably, the ratings assigned to each PSF are independent and do not influence one another.

Step 5 PSF weighting: The weights of PSFs affecting human error are determined according to expert judgment. The designated values for each PSF will differ among experts. A fuzzy number methodology assigns weights to the PSFs, mitigating subjectivity and ambiguity in expert assessments. In this context, experts use the linguistic expressions outlined in Table 1 to demonstrate the relative importance of the PSFs of the relevant process (Chen and Hwang, 1992). At this stage, fuzzy expressions gathered from various expert perspectives are consolidated to yield a singular possibility. The algorithm can be succinctly described in Table 1.

Step 5.1 Obtain data from expert judgement: In the maritime sector, the absence of operational data necessitates the reliance on expert judgments to formulate practical solutions (Lavassani et al., 2015). Expert opinions articulated in linguistic terms can be utilized to assess the probability of each PSF. Hsu and Chen (1996) introduced a

Table 1 Linguistic terms and trapezoidal fuzzy numbers of possibilities

Linguistic term	Fuzzy numbers
Very low (VL)	(0.0, 0.0, 0.1, 0.2)
Low (L)	(0.1, 0.2, 0.2, 0.3)
Medium-low (ML)	(0.2, 0.3, 0.4, 0.5)
Medium (M)	(0.4, 0.5, 0.5, 0.6)
Medium-high (MH)	(0.5, 0.6, 0.7, 0.8)
High (H)	(0.7, 0.8, 0.8, 0.9)
Very high (VH)	(0.8, 0.9, 1.0, 1.0)

methodology for expert elicitation applicable to non-homogeneous groups of experts. The Similarity Aggregation Method (SAM) is a technique that transforms linguistic terms into their associated fuzzy numbers and consolidates the individual assessments provided by experts.

Step 5.2 Calculating the degree of similarity: The similarity degree $S(A_i, A_j)$ between the opinions of two experts, A_i and A_j are assessed. For two Trapezoidal Fuzzy number $A_i = (a_1, a_2, a_3, a_4)$ and $A_j = (b_1, b_2, b_3, b_4)$, the similarity scores can be predicted using equation (2):

$$S(A_i, A_j) = 1 - \frac{1}{4} \sum_{i=1}^4 |a_i - b_i| \tag{2}$$

where, $S(A_i, A_j) \in [0, 1]$. When the value of $S(A_i, A_j)$ approaches 1, there is more similarity between the two fuzzy numbers if both opinions are the same.

Step 5.3 Calculating the average agreement AA(E_i) degree for each expert: In this sub-step, Eq. (3) depicts the average degree of agreement among experts.

$$AA(E_i) = \frac{1}{n-1} \sum_{\substack{j=1 \\ i \neq j}}^n S_{ij}(A_i, A_j) \tag{3}$$

where “ n ” represents the total number of experts.

Step 5.4 The relative agreement RA(E_i) degree, of all experts: Equation (4) is used to compute the experts’ relative agreement degree.

$$RA(E_i) = \frac{AA(E_i)}{\sum_{i=1}^n AA(E_i)} \tag{4}$$

Step 5.5 Predict consensus coefficient degree $C(E_i)$ of experts: To anticipate the consensus coefficient degree of experts $E_i (i = 1, 2, 3, \dots, n)$, utilize equation (5).

$$C(E_i) = \beta \cdot w(E_i) + (1 - \beta) \cdot RA(E_i) \tag{5}$$

where $\beta (0 \leq \beta \leq 1)$ is a relaxation factor.

Step 5.6 The aggregate result of the experts’ judgements: This phase of the SAM involves the aggregation of the experts’ judgements (AG). The equation (6) is utilized in the calculation process.

$$\tilde{R}_{AG} = \sum_{u=1}^M CC(E_u) X\tilde{R}_u \tag{6}$$

where R_{AG} is an aggregate fuzzy number of PSF.

Step 5.7 Defuzzifying of aggregated expert judgement: Finally, in the defuzzification phase, a crisp value is established to signify the aggregate fuzzy number. A Centre of Area (COA) method utilizing the centroid formula is employed to elucidate the fuzzy number (Sugeno, 1999). The defuzzification of the aggregated trapezoidal fuzzy number $A_i = (a_1, a_2, a_3, a_4)$ is defined as:

$$X^* = \frac{1}{3} \times \frac{(a_4 + a_3)^2 - a_4 a_3 - (a_1 + a_2)^2 + a_1 a_2}{(a_4 + a_3 - a_2 - a_1)} \tag{7}$$

Step 6 Determination of SLI: Upon determining the rating and weighting of PSFs, the SLI value is derived using equation (8). SLI is a crucial instrument for predicting the probability of occurrences where several human errors may transpire.

$$SLI = \sum_{i=1}^n r_i w_i, 0 \leq SLI \leq 1 \tag{8}$$

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

Step 7 HEP calculation: Upon determining the SLI value, HEP values can be computed for each task identified in the operation. SLI values can be transformed into HEP values utilizing equation (9), wherein a and b are constants derived from the HEPs corresponding to the subtasks with the highest and lowest SLIs (Embrey et al., 1984).

$$\log(\text{HEP}) = aSLI + b \tag{9}$$

3 Human error in chemical tanker tank heating operation

The proposed method is utilized to assess the tank heating operation of chemical tankers. This procedure may present considerable dangers to the lives of the ship’s crew, port infrastructure, and the marine ecosystem.

3.1 Chemical tankers tank heating operation

The techniques for heating cargo on chemical tankers are vital for maintaining the cargo temperature within defined limits to retain its chemical qualities and assist the

unloading operation. Heating systems, mostly employing heat exchanger technology, control the temperature conditions of several chemical cargoes (ABS, 2020). Stringent regulations govern these processes to avert heat degradation, equipment malfunctions, or other operational risks. The heat exchanger system comprises a series of coils or plates situated within the cargo tanks. Hot water or thermal oil, heated by the boiler or thermal oil system, passes through the coils, indirectly transferring thermal energy to the load (Cargo Heating, 2022).

Although a routine procedure, cargo heating entails considerable hazards owing to its dependence on manual modifications, system calibration, and real-time oversight. Errors such as mismanagement of system pressures, failure to detect leaks, or inadequate monitoring of cargo temperatures can lead to catastrophic consequences such as tank damage, cargo contamination, or explosions (DNV GL, 2019). Improper handling of chemical tanker cargo tanks poses significant operational and safety risks. Overheating may cause excessive vaporization, leading to fire hazards, while insufficient heating can result in solidification, making cargo unloading difficult. Additionally, the mismanagement of heating valves and pressure control systems can lead to thermal stress, equipment failure, or even tank ruptures. A notable example is the explosion aboard the chemical tanker *Stolt Groenland* in Ulsan, South Korea, on 28 September 2019. The incident was caused by a runaway polymerization of styrene monomer, which was inadvertently heated due to improper cargo stowage and inadequate temperature monitoring (MAIB, 2021). Despite being separated from directly heated cargo, the tank received heat transfer through adjacent tanks, leading to a critical temperature rise beyond safe limits. The lack of temperature monitoring and failure to act upon warning signs further exacerbated the situation, ultimately resulting in a catastrophic explosion and fire (MAIB, 2021). Similar incidents have occurred in the past, such as the *Stolt Focus* case, where polymerization was detected in time, preventing an explosion, and the *Bow Mariner* disaster in 2004, where improper handling of chemical cargo tanks led to an explosion and the loss of 21 lives (NTSB, 2005).

Operational protocols must be strictly followed to reduce

onboard risks, and crew training must be provided for potential hazards. Familiarization with system components, regular checks, and rapid response to deficiencies are critical to heat exchanger systems' safe and efficient operation. Regulatory frameworks such as the International Safety Management (ISM) Code guide integrating safety practices into ship operations, while operator-based procedures aim to address systems-specific risks.

3.2 Problem definition

Chemical tanker tank heating operations are performed through operation steps such as temperature regulation, flow control, system maintenance, all of which are significantly influenced by human factors related to safety and efficiency. These operations commonly utilize hot water heat exchanger systems, where water heated by a boiler circulates through a network of stainless steel coils inside the cargo tanks, ensuring gradual and controlled thermal transfer to the cargo. While this method minimizes thermal stress and prevents sudden temperature fluctuations, it also requires precise human intervention. A schematic representation of the tank heating system is provided in Figure 1. Errors such as incorrect valve positioning, improper flow rate adjustments, or failure to detect system malfunctions can result in inadequate heating, cargo contamination, or damage to the heat exchanger system.

International regulations establish a framework for enhancing safety in tank heating activities. However, the constraint of human reliability assessment remains considerable. Although established best practices frequently prioritize mechanical reliability and regulatory adherence, the crucial role of human factors in preventing incidents has not been previously examined (Wu et al., 2023; Magazinović, 2019; Pivac I. and Magazinović, 2015)

This study aims to evaluate the probabilities of human error in cargo tank heating procedures utilizing heat exchangers on chemical tankers. It seeks to identify tasks with a high likelihood of human error and propose strategies for risk mitigation. This approach seeks to enhance the dependability of tank heating procedures while safeguarding both the cargo and the environment.

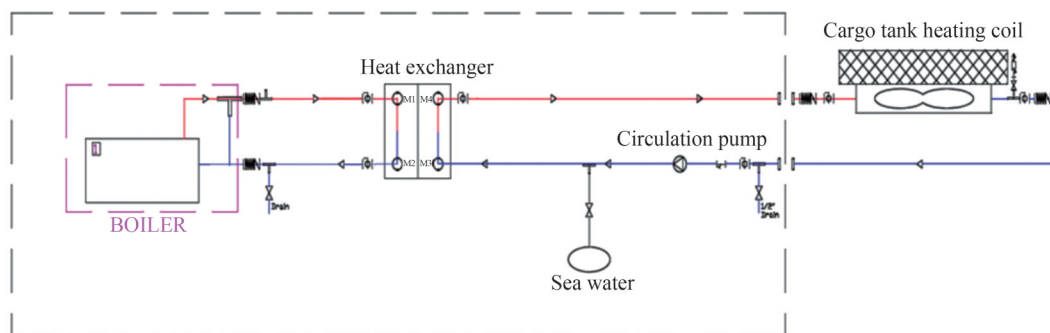


Figure 1 Schematic representation of the cargo tank heating system

3.3 HEP prediction for tank heating operation

HEP estimation for cargo tank heating operation starts with the execution of HTA. The tank heating process on chemical tankers using a heat exchanger can be broadly classified into three main stages: before heating, during heating, and after heating operations. This operation requires full cooperation with the crew and has to be carried out with utmost care in every stage of the operation. The requirements for safety and quality needed during the operation are set by the International Safety Management (ISM) Code, International Safety Guide for Oil Tankers and Terminals (ISGOTT), Tanker Safety Guide Chemicals. Table 2 lists the HTA of the chemical tanker tank heating operation. The HTA is created according to expert opinions and company operation manuals. According to the scenario, palm kernel stearin is transported as cargo during the winter months. The voyage of the vessel consists of loading at a port in Asia and discharging at a port in Northern Europe. During the transport phase, the temperature of the cargo has to be maintained around 35 °C and the temperature of the cargo has to be raised to around 40 °C at the discharge port. The crew comprised two different nationalities onboard and rested adequately. The operation involves the operational responsibilities of the chief officer, chief engineer, deck officers, bosun, and pumpman. The heat exchanger system is used in operation to prevent the loss of the cargo's viscosity and to ensure that it remains pumpable. The system works by circulating hot water to the coils in the tank and transferring heat evenly to the cargo tank.

Six experts were included in the study where expert judgments were used for analyzes. Maritime experts consist of academicians, captains, second officers and chief engineers. Maritime experts have chemical tanker experience and have knowledge of cargo tank heating operations with heat exchanger methods. Equal weights were assigned to experts in the study. In the paper, eight PSFs are used for the evaluation of tank heating operations (Table 3). PSFs are obtained from the literature (Tekeli et al., 2024). Experts evaluate the effects of each obtained PSF for each subtask from 1 to 9. After collecting the ratings of all PSFs for each subtask from the experts, the final rating for each PSF is determined employing the geometric mean. Table 4 presents the PSF ratings of all subtasks evaluated by experts.

In the next step, the PSFs are weighted using a fuzzy approach to address data scarcity and enhance the robustness of the SLIM method. This weighting process is performed according to the linguistic terms in Table 1. The experts weigh each PSF using the linguistic scale given in Table 1. The evaluations of the experts for the PSFs are given in Table 5. The expressions given in the linguistic scale are converted to numerical data using equations (2)–(6) and then crisp values are obtained through equation (7). Then, the crisp values of the PSFs are normalized.

Table 2 The HTA of the tank heating operation

1		Before heating operation
1.1	Inspect the heat exchanger system, hot water pipes and valves visually	
1.2	Verify the pressure and temperature indicators of the hot water circuit	
1.3	Check the temperature requirements and tolerance values of the cargo to be heated from the MSDS documents	
1.4	Determine the maximum and minimum temperature values according to the chemical properties of the cargo	
1.5	Examine the system for signs of leakage or corrosion	
2		During heating operation
2.1	Start the heating boiler and ensure the hot water is within the specified temperature range	
2.2	Open the air vent valves in the heat exchanger pipeline and release the air in the system	
2.3	Open the main and auxiliary valves directing the hot water flow gradually	
2.4	Check the flow rate and pressure of the hot water reaching the cargo tank	
2.5	Direct the hot water from the heat exchanger system to the coils in the cargo tank	
2.6	Perform the temperature increase gradually and prevent sudden temperature increases	
2.7	Monitor the temperature and pressure values at the heat exchanger outlet	
2.8	Prevent fluctuations in the hot water flow rate and maintain a constant flow rate	
2.9	Monitor the alarms or warnings coming from the system	
2.10	Regularly measure the temperature in the tank and ensure that it remains within the specified ranges	
2.11	Monitor the pressure values at the inlet and outlet of the heat exchanger system	
3		After heating operation
3.1	Stop the hot water flow gradually and let the system cool down	
3.2	Discharge the hot water in the heat exchanger system	
3.3	Clean the heating pipes and heat exchanger system	
3.4	Drain the remaining water in the circuit	

Table 3 Nominated PSFs for tank heating operations

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

Table 4 Nominated PSFs for tank heating operations

Sub-task	Stress	Complexity	Training	Experience	Time availability	Environmental factors	Communication	Safety culture
1.1	3.5	2.7	3.2	4.2	5.4	5.8	3.6	3.4
1.2	3.3	3.9	2.9	3.2	5.0	5.6	3.7	2.7
1.3	4.4	3.2	2.7	2.6	4.7	5.3	4.3	3.1
1.4	3.9	3.5	2.7	3.2	5.0	5.4	5.1	3.5
1.5	3.6	4.2	3.0	2.6	4.3	4.7	4.2	3.7
2.1	3.4	4.5	3.4	3.9	4.9	5.0	5.0	3.8
2.2	3.2	4.4	3.5	3.7	4.8	5.2	4.9	3.2
2.3	3.0	3.2	3.1	3.7	4.6	5.6	3.9	3.5
2.4	3.8	2.9	3.3	3.4	5.5	4.6	3.6	3.1
2.5	3.2	4.4	3.2	2.9	4.8	5.8	4.5	2.7
2.6	3.6	3.3	3.6	2.6	4.8	4.3	3.7	2.6
2.7	3.6	3.8	3.1	3.7	5.3	4.2	4.2	3.0
2.8	3.3	3.5	3.4	3.7	5.2	4.9	4.9	2.5
2.9	3.3	4.5	3.6	2.6	5.3	5.1	4.4	3.4
2.10	2.9	3.5	3.1	4.3	5.3	4.2	4.5	3.5
2.11	3.5	3.2	3.0	3.9	5.5	5.6	5.0	3.1
3.1	3.5	3.1	3.5	4.0	5.1	5.4	4.1	2.7
3.2	3.7	4.0	3.7	3.6	5.6	6.1	5.1	3.4
3.3	3.6	3.6	3.4	3.4	5.3	6.0	4.2	2.7
3.4	3.2	3.3	3.2	3.5	4.5	5.7	5.3	2.9

Table 5 Linguistic evaluations of six marine experts for each PSF

Expert	PSF1	PSF2	PSF3	PSF4	PSF5	PSF6	PSF7	PSF8
E1	H	H	M	MH	M	H	ML	H
E2	MH	VH	MH	MH	M	VH	H	MH
E3	H	MH	VH	M	MH	H	MH	H
E4	M	MH	MH	H	ML	MH	H	VH
E5	H	H	H	MH	ML	H	MH	H
E6	VH	VH	H	MH	L	VH	M	MH

The collected fuzzy numbers, crisp values and normalized weight of each PSF are shown in Table 6. On the other hand, the weight calculation of PSF2 (Complexity) is given as an example in Table 7.

Then, using equation (8), SLIs are calculated for each subtask of the operation. HEP values are obtained from the SLI values with equation (9). To determine the constants *a* and *b* in equation (9), experts estimate the best and worst-case scenarios during the operation and the limits are determined. Based on expert consensus, the limits are defined as $SLI = 9, HEP = 10^{-4}$ for the best-case scenarios, and

Table 6 PSF weights based on fuzzy numbers

PSF	Aggregated fuzzy numbers	CV	Normalized value
Stress	(0.637, 0.737, 0.770, 0.854)	0.748	0.134
Complexity	(0.667, 0.768, 0.834, 0.901)	0.791	0.142
Training	(0.601, 0.701, 0.751, 0.835)	0.721	0.129
Experience	(0.516, 0.616, 0.684, 0.784)	0.650	0.117
Time availability	(0.300, 0.400, 0.450, 0.550)	0.425	0.076
Environmental factors	(0.702, 0.802, 0.851, 0.918)	0.816	0.147
Communication	(0.504, 0.604, 0.654, 0.754)	0.629	0.113
Safety culture	(0.650, 0.751, 0.800, 0.884)	0.770	0.138

$SLI = 1, HEP = 0.90$ for the worst-case scenarios. These limits are substituted into the equation (9). Thus, the constants *a* and *b* are obtained by solving the two equations simultaneously (Sezer et al., 2023, Tekeli et al., 2024, Abrishami et al., 2020). For this study, the calculated values are $a = -0.494$ and $b = 0.449$. Table 8 shows the SLI and HEP values for each subtask.

Table 7 Weight calculation process of PSF 2

Experts' opinions on the importance of PSF2			
Expert	Evaluation	Fuzzy numbers	
E1	H	(0.7, 0.8, 0.8, 0.9)	
E2	VH	(0.8, 0.9, 1.0, 1.0)	
E3	MH	(0.5, 0.6, 0.7, 0.8)	
E4	MH	(0.5, 0.6, 0.7, 0.8)	
E5	H	(0.7, 0.8, 0.8, 0.9)	
E6	VH	(0.8, 0.9, 1.0, 1.0)	
Similarity functions for PSF2			
S(E1&E2)		0.875	
S(E1&E3)		0.850	
S(E1&E4)		0.850	
S(E1&E5)		1	
S(E1&E6)		0.875	
S(E2&E3)		0.725	
S(E2&E4)		0.725	
S(E2&E5)		0.875	
S(E2&E6)		1	
S(E3&E4)		1	
S(E3&E5)		0.850	
S(E3&E6)		0.725	
S(E4&E5)		0.850	
S(E4&E6)		0.725	
S(E5&E6)		0.875	
AA, RA and CC values of marine experts for PSF2			
Expert	Average agreement (AA)	Relative agreement (RA)	Consensus coefficient (CC)
E1	0.89	0.17	0.170
E2	0.84	0.16	0.166
E3	0.83	0.16	0.165
E4	0.83	0.16	0.165
E5	0.89	0.17	0.170
E6	0.84	0.16	0.166
Aggregated experts' opinions		(0.667, 0.768, 0.834, 0.901)	
Crisp value		0.791	
Normalised value		0.142	

Note: $\beta = 0.5$ (Senol et al., 2015; Elidolu et al., 2022a)

4 Findings and discussions

In this study, the fuzzy SLIM method was applied to evaluate the probability of human error (HEP) during the

Table 8 Calculated SLI and HEP values for each sub-task

Sub-tasks	SLI	Log (HEP)	HEP
1.1	3.893	-1.47619	3.34E-02
1.2	3.754	-1.40715	3.92E-02
1.3	3.761	-1.41082	3.88E-02
1.4	3.976	-1.51688	3.04E-02
1.5	3.782	-1.42124	3.79E-02
2.1	4.180	-1.61771	2.41E-02
2.2	4.072	-1.56444	2.73E-02
2.3	3.781	-1.42075	3.80E-02
2.4	3.664	-1.36261	4.34E-02
2.5	3.920	-1.48936	3.24E-02
2.6	3.491	-1.27740	5.28E-02
2.7	3.769	-1.41465	3.85E-02
2.8	3.814	-1.43672	3.66E-02
2.9	3.961	-1.50957	3.09E-02
2.10	3.817	-1.43861	3.64E-02
2.11	4.005	-1.53152	2.94E-02
3.1	3.877	-1.46801	3.40E-02
3.2	4.336	-1.69501	2.02E-02
3.3	3.981	-1.51947	3.02E-02
3.4	3.890	-1.47429	3.36E-02

tank heating operation of chemical tankers. A total of 20 subtasks were evaluated with expert judgments. According to the calculation results, the subtask with the highest probability of error is sub-task 2.6, which performs the temperature increase gradually and prevents sudden temperature increases (HEP: 5.28E-02). Sudden temperature increases can cause operational hazards by causing thermal stress or cargo damage. In addition, sudden temperature increases in chemical tankers can cause serious risks such as fire and explosion, as they can cause the formation of flammable vapors or the pressure inside the tank to reach critical levels. To reduce human errors, increasing awareness during operations, regularly monitoring alarms and warnings, and being familiar with the systems are very important. In addition, in the future, automating temperature control systems and providing operators with advanced real-time data visualization can be an innovative approach to preventing human errors.

The sub-task with the second highest HEP value is 2.4 Check the flow rate and pressure of the hot water reaching the cargo tank (HEP: 4.34E-02). Correct flow rate and pres-

sure values ensure that the hot water transferred to the cargo tank works effectively. Keeping the tanks at the desired temperature is directly related to the success of this task. Insufficient flow rate or excessive pressure can prevent the cargo from reaching the desired temperature level and cause delays in operation. It can also cause damage to pipelines, valves and heating systems. This can cause system failures and create financial burdens. Periodic calibration of flow meters and pressure sensors, planned maintenance and elimination of deficiencies, training to interpret and respond to abnormalities, and operational familiarization can reduce human errors.

The next highest HEP value is sub-task 1.2 Verify the pressure and temperature indicators of the hot water circuit (HEP: 3.92E-02). The reliability of temperature and pressure indicators in the hot water circuit is crucial for safe tank heating operation. Inaccurate data from these indicators jeopardizes the entire operation. For this purpose, the indicators should be maintained regularly. Redundant systems can be used to compare data from different indicators during operation. In addition, integrating the indicators with a digital system can allow instant data analysis, reducing the probability of errors by the officer in charge. The sub-task 1.3 with the highest HEP value is Checking the temperature requirements and tolerance values of the cargo from the MSDS documents (HEP: 3.88E-02). Maintaining cargo-specific temperature tolerances is vital for operational and environmental safety. Errors in this task are often linked to inadequate understanding or misinterpretation of the MSDS (Material Safety Data Sheet). Providing specific training focused on cargo-specific requirements, ensuring that personnel have experience interpreting this material, and creating digitalized platforms with integrated decision support systems can help minimize human errors during operations.

Monitoring the temperature and pressure values at the heat exchanger outlet (sub-task 2.7) is one of the critical tasks in the tank heating process (HEP: 3.85E-02). Keeping these parameters under control ensures that the heat transfer takes place as desired and minimises maintenance and repair costs by preventing damage to the equipment. In this context, the selection of appropriate technologies for the task and the rigorous implementation of operating procedures are necessary. A monitoring system integrating modern sensors, automation systems and alarm mechanisms enables instant control of these values and rapid intervention in case of deviation.

In line with the findings, experts emphasise that temperature management in chemical cargo operations must be meticulous and that automation systems can play a critical role in minimising human error. Due to the tight temperature tolerances of chemical cargoes, the integration of automated monitoring and alarm systems as well as manual controls is of great importance. In addition, some experts

emphasise that the ability of the operations team to interpret sensor data is also a critical element. Misunderstanding or neglecting data from sensors can lead to operational errors. Therefore, the crew should receive regular training and be able to effectively evaluate the warnings provided by the systems. It is also noted that technical factors such as sensor failures or inaccurate measurements can also affect the HEP value and therefore reliability analyses should be carried out regularly. Finally, while experts recognise that automation systems are an important tool in reducing human error, they also emphasise that it is not possible to create a process that is completely independent of the human factor. Therefore, in addition to automation, it is stated that enhancing the human factor and increasing operational awareness will be a more effective approach to reducing the overall error rate.

5 Comparison with an extended CREAM

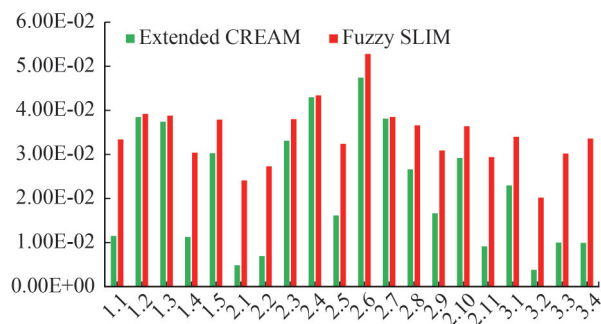
To evaluate the effectiveness and validity of the used method, the obtained HEP results are compared with those from CREAM, a widely used approach in HRA. CREAM, introduced by Hollnagel (Hollnagel, 1998), provides a cognitive framework for estimating human error probabilities in specific tasks. The extended CREAM methodology involves several key steps: i) Assessing Common Performance Conditions (CPC), ii) Determining the Context Influence Index (CII), iii) Establishing the Performance Influence Index (PII), and iv) Estimating the Cognitive Failure Probability (CFP). The equation (10) is employed in CREAM to compute HEP (He et al., 2008; Arici et al., 2024).

$$CFP = CFP_0 \times 10^{0.26 \cdot CII} \quad (10)$$

The CFP_0 in equation (10) represents the nominal values provided for cognitive function failures. The HEP values calculated according to Equation (10) are listed in Table 9. The dataset is obtained from the consensus of maritime experts with substantial expertise in chemical tanker operations and maritime safety. In light of the comparison, the results calculated with the fuzzy SLIM approach and the extended CREAM approach are quite close. This may partially validate the model. In light of the comparison, the results calculated with the fuzzy SLIM approach and the extended CREAM approach are quite close. This may partially validate the model. Figure 2 illustrates the comparison of HEP values. Furthermore, the results obtained from the fuzzy SLIM approach are compared with the judgments based on experts' experience and found to be in harmony with their professional assessments.

Table 9 HEP estimation based on the extended CREAM

Sub-task	Cognitive activity	Cognitive function	Generic failure type	Nominal CFP (CFP ₀)	Adjusted CFP
1.1	Execute	Missed action	E5	3.00E-02	1.15E-02
1.2	Verify	Wrong identification	O2	7.00E-02	3.85E-02
1.3	Evaluate	Faulty diagnosis	I1	2.00E-01	3.74E-02
1.4	Diagnose	Decision error	I2	1.00E-02	1.13E-02
1.5	Verify	Observation not made	O3	7.00E-02	3.03E-02
2.1	Execute	Action of wrong type	E1	3.00E-03	4.84E-03
2.2	Execute	Action at wrong time	E2	3.00E-03	6.94E-03
2.3	Evaluate	Decision error	I2	1.00E-02	3.31E-02
2.4	Execute	Missed action	E5	3.00E-02	4.30E-02
2.5	Diagnose	Decision error	I2	1.00E-02	1.61E-02
2.6	Evaluate	Delayed interpretation	I3	1.00E-02	4.74E-02
2.7	Monitor	Wrong identification	O2	3.00E-02	3.81E-02
2.8	Execute	Missed action	E5	3.00E-02	2.66E-02
2.9	Monitor	Observation not made	O3	7.00E-02	1.66E-02
2.10	Execute	Action out of sequence	E4	3.00E-03	2.92E-02
2.11	Monitor	Wrong identification	O2	7.00E-02	9.14E-03
3.1	Execute	Action out of sequence	E4	3.00E-03	2.30E-02
3.2	Execute	Action at wrong time	E2	3.00E-03	3.81E-03
3.3	Execute	Missed action	E5	1.00E-02	1.00E-02
3.4	Execute	Action out of sequence	E4	3.00E-03	9.93E-03

**Figure 2** HEP value comparison plot

6 Conclusion

Tank heating operations with heat exchanger systems in chemical tankers are processes that require precision and have critical importance in terms of operational safety, as they prevent the physical and chemical properties of the cargo from deteriorating and ensure that the cargo remains at the desired values. This study evaluated human reliability using SLIM and a fuzzy logic-based approach. As a result, tasks such as preventing sudden temperature increases, controlling the flow rate and pressure of hot water, verifying the indicators of the hot water circuit, and checking the cargo temperature requirements from MSDS documents were calculated as the tasks with the highest HEP value.

Successfully completing these tasks is the basic building block of the operation's success. These errors can lead to serious risks and negative consequences, such as equipment failures, cargo damage, and fire or explosion. Therefore, both technological and process-oriented approaches are required to increase operational reliability.

Unlike studies, which are focused on maritime operations such as navigation, cargo handling, and emergency response, cargo tank heating operations present unique challenges that require constant monitoring and precise control. Errors in traditional maritime tasks often have immediate consequences and prompt rapid corrective action. However, errors in chemical tanker tank heating operations (such as improper temperature control or flow regulation) can develop gradually and lead to short-term and long-term safety risks. This highlights the need for a dedicated human error assessment framework specifically designed for chemical tanker cargo tank heating, ensuring that the complexities of long-term system monitoring and thermal regulation are accounted for.

This study contributes to the existing literature by addressing a gap in human error analysis for chemical tanker tank heating operations and presents an approach to integrating SLIM and fuzzy logic in tank heating. Also, this research expands the method's applicability by presenting a task-specific risk assessment framework tailored to the complexities of long-term thermal regulation. The findings of

this study offer valuable insights for maritime authorities, owners of chemical tanker vessels, and safety researchers, contributing to the enhancement of onboard safety measures for chemical tanker operations.

Practical training programs, development of standard operational checklists, real-time monitoring and integration of automation systems are tools that can reduce human error in tank heating operations and increase operational efficiency. Future studies can further investigate integrating innovative technologies such as augmented reality (AR) and digital twins into operational support and training processes to increase human reliability. In addition, by including larger data sets and expert opinions, the accuracy of the model can be increased, and more robust results can be obtained by integrating highly reliable methods based on expert judgements, such as the evidential reasoning and improved Z number. Besides, how the differences in expert opinions can be addressed and the applicability of the group SLIM method can be examined in more detail. Such systematic approaches provide an important roadmap to increase operational safety and lead to more sustainable practices.

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