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Assessment of human error contribution to container loss risk under fault tree analysis and interval type-2 fuzzy logic-based SLIM approach.

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Abstract

Human is a key element of the safety of life on board ships and a significant contributing factor to most of the accidents and incidents in the maritime industry. At this point, risk analysis plays a critical role in ensuring operational safety and maritime transportation sustainability. This paper aims to systematically evaluate how human errors (HEs) contribute to operational risks. Based on this, Fault Tree Analysis (FTA) is combined under an Interval Type-2 Fuzzy Logic environment with Success Likelihood Index Method (SLIM). Whilst the FTA evaluates the criticality of the operational activities, the Interval Type-2 Fuzzy Sets (IT2FS) deals with vagueness and subjectivity in using experts' judgments, and the SLIM estimates the probabilities for the human error-related basic events. Since container losses can lead to severe damage and catastrophic events in a container terminal, loading operation was investigated as a case study. Safety culture, experience, and fatigue were observed as highly effective factors in crew performance. The obtained results also indicate that this hybrid approach can effectively be applied to determine the operational vulnerabilities in high-risk industries. The paper intends to improve safety control levels and lower losses in the future of maritime container transport besides emphasizing the potential consequences of failures and crucial human errors in the operational process.

Keywords: Human error**,** risk analysis, IT2Fs, SLIM, FTA, container loss.

1. Introduction

More than 100 million containers are shipped across the globe on containerships per year. According to containerised trade data, the number reached approximately 160.5 million containers in 2019 [1]. Based on this, container transportation has become even more important for global maritime trade. However, significant container shipping disasters where hundreds of containers were lost in a single event have occurred in recent years [2]. The disastrous fires and explosions on Maersk Honam [3,4], MSC Flaminia [5,6], Hyundai Fortune [6,7], and Hanjin Pennsylvania [6,8,9], hull fracture on MSC Napoli [5, 10, 11] and hull girder fracture on Mol Comfort [5,12], and the breaking of Rena in two [13,14] , collapsed and fallen overboard containers on MSC Zoe [15,16] have caused the worst maritime environmental disasters in the last decade. Besides the loss of containers severely damaging the marine environment, tragically, some crew members have died because of the accidents.

Each operational activity carried out onboard ships includes risks due to the nature of the work. Therefore, identifying the risk factors and minimising them to an acceptable level is paramount to enhancing the safety level [17]. Human error, technical, mechanical, structural failure, and environmental factors are common causes of marine accident risk [18]. As the regulatory body, International Maritime Organization (IMO) emphasises that the human factor plays a crucial role in accidents [19]. The statistics show that more than 80 percent of shipping casualties are directly related to human error [20,21,22]. Thereby, human error contribution should be the core point of the quantitative risk analysis (QRA) in maritime operations. A variety of approaches that focus on human error probability (HEP) quantifications have also been implemented in different industries such as offshore [23,24,25,26, 27], aviation [28], railway [29, 30, 31, 32], nuclear power plants [33,34, 35], and mining [36].

The maritime industry seeks to reduce losses in the future. However, risk assessments carried out apart from the crew safety performance shall be insufficient in analysing the potential threats. At this point, some impact factors related to the task, individuals or working environment should also be considered while evaluating the HEPs. These relative factors [37], called performance shaping factors (PSFs), are of paramount influence on human performance negatively or positively [32].

The SLIM technique considering HEP assessments has been used to determine the human error contribution to operational risks [22,37,38,39,40] in the maritime transportation industry. In this study, a quantitative risk analysis is performed by considering the possible human errors in the container loading operation process. In this context, this paper proposed a hybrid approach by incorporating Fault Tree Analysis (FTA) and Interval type-2 fuzzy-based SLIM to evaluate the human contribution to risks and the criticality of the loading operation activities in a container terminal. To achieve this goal, the paper is structured as follows: The first part presents the motivation behind the study and basic literature review on significant container shipping disasters. Because of the substantial role of each method in the study, a brief literature review and the theoretical background of the methods are provided in section 2. Section 3 offers the integration of the proposed approach, while Section 4 illustrates the exemplificative application of the proposed approach to risk of container loss in maritime transportation. Findings and extended discussion are presented in section 5. Finally, the conclusion and research contribution to maritime transport is included in the last section.

2. Methods

The hybrid approach is proposed to determine the contribution of human error to the risks related with the most critical vulnerabilities in the operational processes. In this context, the SLIM estimates the HEPs whilst the FTA perform a comprehensive risk assessment. Since there is an ambiguity with the crisp value of probability, the IT2FS deals with vagueness and subjectivity in using experts' judgements [41,42,43].

2.1 IT2FS

The concept of a type-2 fuzzy set was first introduced by Zadeh [44] as an extension of the idea of a conventional fuzzy set called a type-1 fuzzy set (T1FS) [42,45]. A fuzzy set states the degree to which an element belongs to a set. In case it is not possible to determine the membership of an element in a set as 0 or 1, the type 1 or type 2 fuzzy sets are utilised. The membership grade for each element of the type-2 fuzzy set (T2FS) is a fuzzy set in [0,1]. On the other hand, a type-1 is a fuzzy set where a membership grade is a crisp number in [0,1] [46, 47]. The basic principle behind systems is the same for both Type-1 and Type-2. However, T2FS can better express a higher degree of fuzziness and provides more various parameters than T1FS [46,81].
An interval type-2 fuzzy set (IT2FS) is a special case of the generalised T2FS [42] in which the membership grade of every domain point is a crisp set whose domain is some interval contained in [0,1] [45]. Mendel [48] proposed the interval type-2 fuzzy set to describe an imprecise linguistic term, linguistically and quantitatively [49]. The data collected from the experts' linguistic expressions are subjective and have limitations. At this point, the IT2FS can cope with complex conditions and reflects uncertainties better [50,51,52]. IT2FS is rather adequate for utilising in real-

case applications compared to generalised T2FS [53] and is commonly used in decision-making problems [54,55]. The IT2FS is applied almost all problems by reason of their reduced computational effort and feasibility [41,45]. Following a description of the T2FS and the IT2FS, the below equations present the mathematical operations' definitions and step-by-step developments, respectively.

Definition 1: A type-2 fuzzy set $\tilde{\tilde{A}}$ in the universe of discourse *X* can be characterised by a type-2 membership function $\mu_{\tilde{\tilde{A}}}(x,u)$, where J_X denotes an interval in [0, 1] is illustrated as follows [47]:

$$\tilde{\tilde{A}} = \{((x,u),\mu_{\tilde{\tilde{A}}}(x,u)) | \forall x \in X, \forall u \in J_X \subseteq [0,1], 0 \leq \mu_{\tilde{\tilde{A}}}(x,u) \leq 1\}$$

In addition, the type-2 fuzzy set $\tilde{\tilde{A}}$ can also be represented as follows when the elements of the fuzzy numbers are continuous [47]:

$$\tilde{\tilde{A}} = \int_{x \in X} \int_{u \in J_X} \mu_{\tilde{\tilde{A}}}(x,u)/(x,u) = \int_{x \in X} \left(\int_{u \in J_X} \mu_{\tilde{\tilde{A}}}(x,u)/u \right) /x$$

Where $J_X \subseteq [0,1]$ and $\iint$ denotes union over all admissible *x* and *u*.

Definition 2: Let $\tilde{\tilde{A}}$ be a type-2 fuzzy set in the universe of discourse *X* represented by the type-2 membership function $\mu_{\tilde{\tilde{A}}}(x,u)$. If all $\mu_{\tilde{\tilde{A}}}(x,u) = 1$, then $\tilde{\tilde{A}}$ is called an interval type-2 fuzzy set and represented as follows [46,47]:

$$\tilde{\tilde{A}} = \int_{x \in X} \int_{u \in J_X} 1/(x,u) = \int_{x \in X} \left(\int_{u \in J_X} 1/u \right) /x ,$$

where $J_X \subseteq [0,1]$.

Definition 3: A method utilising the IT2FSs for tackling fuzzy multiple attribute group decision-making problems are presented in this study. In this model, the heights of the upper and the lower membership functions of the IT2FSs and the reference points are characterised as a trapezoidal IT2FS as shown in Figure 1 [47].

<Figure 1> is inserted here.

A trapezoidal interval type-2 fuzzy set:

$$\tilde{\tilde{A}}_i = (\tilde{A}_i^U, \tilde{A}_i^L) = \left(\left(a_{i1}^U, a_{i2}^U, a_{i3}^U, a_{i4}^U; H_1(\tilde{A}_i^U), H_2(\tilde{A}_i^U)\right), \left(a_{i1}^L, a_{i2}^L, a_{i3}^L, a_{i4}^L; H_1(\tilde{A}_i^L), H_2(\tilde{A}_i^L)\right)\right)$$

where $\tilde{A}_i^U$ and $\tilde{A}_i^L$ are type-1 fuzzy sets, $a_{i1}^U, a_{i2}^U, a_{i3}^U, a_{i4}^U, a_{i1}^L, a_{i2}^L, a_{i3}^L$ and a_{i4}^L are the reference points of the interval type-2 fuzzy $\tilde{\tilde{A}}_i$; $H_j(\tilde{A}_i^U)$ represents the membership value of the element $a_{i(j+1)}^U$ in the upper trapezoidal membership function, $\tilde{A}_i^U$; $1 \le j \le 2$, $H_j(\tilde{A}_i^L)$ represents the membership value of the element $a_{i(j+1)}^L$ in the lower trapezoidal membership function $\tilde{A}_i^L$; $1 \le j \le 2$, $H_j(\tilde{A}_i^L)$,

$$H_1(\tilde{A}_i^U) \in [0,1],\ H_2(\tilde{A}_i^U) \in [0,1],\ H_1(\tilde{A}_i^L) \in [0,1],\ H_2(\tilde{A}_i^L) \in [0,1] \text{ and } 1 \le i \le n.$$

Definition 4: To rank and defuzzify the IT2FSs an extended centre-of-area method is utilised. Accordingly, the equation (1) is implemented in defuzzification process of the IT2FSs.

$$Defuzzified(\tilde{\tilde{A}}_i) = \frac{\frac{(a_{i4}^U - a_{i1}^U) + (H_1(\tilde{A}_i^U) * a_{i2}^U - a_{i1}^U) + (H_2(\tilde{A}_i^U) * a_{i3}^U - a_{i1}^U)}{4} + a_{i1}^U + \frac{(a_{i4}^L - a_{i1}^L) + (H_1(\tilde{A}_i^L) * a_{i2}^L - a_{i1}^L) + (H_2(\tilde{A}_i^L) * a_{i3}^L - a_{i1}^L)}{4} + a_{i1}^L}{2} \quad (1)$$

Mathematical operations using between two IT2FSs for further calculations are also as given below [41,43,56]:

For the addition operation:

$$\tilde{\tilde{A}}_1 = (\tilde{A}_1^U, \tilde{A}_1^L) = \left(\left(a_{11}^U, a_{12}^U, a_{13}^U, a_{14}^U; H_1(\tilde{A}_1^U), H_2(\tilde{A}_1^U)\right), \left(a_{11}^L, a_{12}^L, a_{13}^L, a_{14}^L; H_1(\tilde{A}_1^L), H_2(\tilde{A}_1^L)\right)\right)$$

$$\tilde{\tilde{A}}_2 = (\tilde{A}_2^U, \tilde{A}_2^L) = \left(\left(a_{21}^U, a_{22}^U, a_{23}^U, a_{24}^U; H_1(\tilde{A}_2^U), H_2(\tilde{A}_2^U)\right), \left(a_{21}^L, a_{22}^L, a_{23}^L, a_{24}^L; H_1(\tilde{A}_2^L), H_2(\tilde{A}_2^L)\right)\right)$$

$$\tilde{A}_1 \oplus \tilde{A}_2 = (\tilde{A}_1^U, \tilde{A}_1^L) \oplus (\tilde{A}_2^U, \tilde{A}_2^L)$$

$$= \begin{pmatrix} \left(a_{11}^U + a_{21}^U, a_{12}^U + a_{22}^U, a_{13}^U + a_{23}^U, a_{14}^U + a_{24}^U; min\left(H_1(\tilde{A}_1^U), H_1(\tilde{A}_2^U)\right), min\left(H_2(\tilde{A}_1^U), H_2(\tilde{A}_2^U)\right)\right), \\ \left(a_{11}^L + a_{21}^L, a_{12}^L + a_{22}^L, a_{13}^L + a_{23}^L, a_{14}^L + a_{24}^L; min\left(H_1(\tilde{A}_1^L), H_1(\tilde{A}_2^L)\right), min\left(H_2(\tilde{A}_1^L), H_2(\tilde{A}_2^L)\right)\right) \end{pmatrix} \quad (2)$$

For the subtraction operation:

$$\tilde{A}_1 \theta \tilde{A}_2 = \left(\tilde{A}_1^U, \tilde{A}_1^L\right) \theta \left(\tilde{A}_2^U, \tilde{A}_2^L\right)$$

$$= \begin{pmatrix} \left(a_{11}^U - a_{21}^U, a_{12}^U - a_{22}^U, a_{13}^U - a_{23}^U, a_{14}^U - a_{24}^U; min\left(H_1(\tilde{A}_1^U), H_1(\tilde{A}_2^U)\right), min\left(H_2(\tilde{A}_1^U), H_2(\tilde{A}_2^U)\right)\right), \\ \left(a_{11}^L - a_{21}^L, a_{12}^L - a_{22}^L, a_{13}^L - a_{23}^L, a_{14}^L - a_{24}^L; min\left(H_1(\tilde{A}_1^L), H_1(\tilde{A}_2^L)\right), min\left(H_2(\tilde{A}_1^L), H_2(\tilde{A}_2^L)\right)\right) \end{pmatrix} \quad (3)$$

For the multiplication operation:

$$\tilde{A}_1 \otimes \tilde{A}_2 = \left(\tilde{A}_1^U, \tilde{A}_1^L\right) \otimes \left(\tilde{A}_2^U, \tilde{A}_2^L\right)$$

$$= \begin{pmatrix} \left(a_{11}^U \times a_{21}^U, a_{12}^U \times a_{22}^U, a_{13}^U \times a_{23}^U, a_{14}^U \times a_{24}^U; min\left(H_1(\tilde{A}_1^U), H_1(\tilde{A}_2^U)\right), min\left(H_2(\tilde{A}_1^U), H_2(\tilde{A}_2^U)\right)\right), \\ \left(a_{11}^L \times a_{21}^L, a_{12}^L \times a_{22}^L, a_{13}^L \times a_{23}^L, a_{14}^L \times a_{24}^L; min\left(H_1(\tilde{A}_1^L), H_1(\tilde{A}_2^L)\right), min\left(H_2(\tilde{A}_1^L), H_2(\tilde{A}_2^L)\right)\right) \end{pmatrix} \quad (4)$$

For the arithmetic operations:

$$k\tilde{\tilde{A}}_1 = \begin{pmatrix} \left(k \times a_{11}^U, k \times a_{12}^U, k \times a_{13}^U, k \times a_{14}^U; H_1(\tilde{A}_1^U), H_2(\tilde{A}_1^U)\right), \\ \left(k \times a_{11}^L, k \times a_{12}^L, k \times a_{13}^L, k \times a_{14}^L; H_1(\tilde{A}_1^L), H_2(\tilde{A}_1^L)\right) \end{pmatrix} \quad (5)$$

$$\frac{\tilde{\tilde{A}}_1}{k} = \begin{pmatrix} \left(\frac{1}{k} \times a_{11}^U, \frac{1}{k} \times a_{12}^U, \frac{1}{k} \times a_{13}^U, \frac{1}{k} \times a_{14}^U; H_1(\tilde{A}_1^U), H_2(\tilde{A}_1^U)\right), \\ \left(\frac{1}{k} \times a_{11}^L, \frac{1}{k} \times a_{12}^L, \frac{1}{k} \times a_{13}^L, \frac{1}{k} \times a_{14}^L; H_1(\tilde{A}_1^L), H_2(\tilde{A}_1^L)\right) \end{pmatrix} \quad (6)$$

2.2 SLIM

The SLIM [57] was first introduced to estimate the probability of success of specific human actions in nuclear power plants [58]. The fundamental rationale of the SLIM is that the success likelihood of a task is based on the combined effects of a set of performance shaping factors (PSFs) which has a considerable influence on human performance [59]. The SLIM is a simple and flexible approach [24, 37, 60] that makes use of domain expert judgment to select and weigh the PSFs according to their perceived contribution in a given task for estimating HEPs [61]. Accordingly, the core and crucial step is the formation of a committee of experts to generate the relevant data reliably. Following the quantification of PSFs, a Success Likelihood Index (SLI) is obtained utilising experts' judgments for each action of the specific task [22,62]. Subsequently, the SLI value is calibrated with the human error data to predict the HEP value. The main steps of the method are expressed as follows: i.) PSF derivation, ii.) PSF rating, iii.) PSF weighting, iv.) SLI determination, v.) HEP calculation

The below equation is utilised in the SLI determination process.

$$SLI = \sum_{i=1}^{n} r_i w_i , \quad 0 \leq SLI \leq 1 \tag{7}$$

In the equation above, n denotes the PSFs' number, r_i denotes the rating scale of PSFs, and w_i denotes the weight of the PSFs' relative importance.

Accordingly, the conversion of the SLIs to HEP values is achieved by a logarithmic relationship represented in equation (8).

$$Log\ (HEP) = aSLI + b \tag{8}$$

In equation (8), a and b are the constants elicited from the HEP values for the sub-tasks with the highest and lowest SLIs [57].

2.3 FTA

Fault Tree Analysis (FTA) is one of the most crucial logic and probabilistic techniques extensively utilised for reliability evaluation and probabilistic risk assessment of complex systems [63,64,65]. The technique generates a mechanism for efficient system-level risk assessments. As a top-down and deductive failure analysis [60], the technique identifies the sub-systems essential for the operation of a complex system [66].
Visualizing a conventional fault tree comprises three major graphic symbols: events, logical gates, and transfer symbols [67,80,82]. Several sequential fault combinations that cause the undesired event called the 'top event' (TE) are depicted at different system levels. The TE is of enormous significance for the complex system due to cause catastrophic consequences for humans, commodity, and the environment [68]. Therefore, a fault tree is directly focused on the top event of the tree. In line with this purpose, the fault tree represents the logical interrelationships of basic events (BEs), which trigger the main event when they co-occur, and employs Boolean algebra rules. These rules are utilised to acquire one form of the fault tree, called the minimal cut set (MCS), that allows qualitative and quantitative assessments to be performed simply. The MCS specifies the system's structural vulnerability [68]. The logical gates utilised to represent the relationships of events express the relationship type of the input events needed for the output event. The quantification of probabilities occurs according to the MCSs describing the relationships between BEs using "AND" and "OR" gates. Accordingly, the

equation (9) is utilised to obtain the occurrence probability of the top event associated with the "AND" gate, where P expresses the occurrence probability of the top event, n expresses the number of the BEs and pi expresses the occurrence probability of basic event i.

$$P = \prod_{i=1}^{n} pi \tag{9}$$

Associated with the "OR" gate event, the equation (10) is utilised to acquire the top event's occurrence probability:

$$P = 1 - \prod_{i=1}^{n} (1 - pi) \tag{10}$$

The MCSs and overall failure probability of the top event are needed to calculate once the occurrence probabilities of BEs and IEs are gathered. The following equations are used for MCSs [69,70].

$$TE = MCS_1 + MCS_2 + \ldots + MCS_N = \bigcup_{i=1}^{n_c} MCS \tag{11}$$

The below equations are utilised to calculate the occurrence probability of TE [70,71].

$$\begin{aligned} P(T) &= P(MCS_1 \cup MCS_2 \cup \ldots \cup MCS_N) \\ &= P(MCS_1) + P(MCS_2) + \ldots P(MCS_N) - (P(MCS_1 \cap MCS_2) \\ &+ P(MCS_1 \cap MCS_3) + \ldots P(MCS_i \cap MCS_j) \ldots) \ldots \\ &+ (-1)^{N-1} P(MCS_1 \cap MCS_2 \cap \ldots \cap MCS_N) \end{aligned} \tag{12}$$

In the FTA technique, the FV-I (Fussell Vesely Importance Measure) method is utilised to ascertain the importance value of BEs and MCs constructing the TE [72,73]. The following equation is used for the FV-I.

$$I_i^{VF}(t) = \frac{Q_i(t)}{Q_s(t)} \tag{13}$$

where I_i is the importance degree of MCS, $Q_i(t)$ occurrence probability value of MC_i and $Q_S(t)$ states occurrence probability of TE in all MCS [74].

3. Integration of methodologies

The integration of methodologies for comprehensive risk analysis is provided in this section. The FTA is combined with the IT2FS-SLIM approach. In this context, Figure 2 illustrates the conceptual framework of the integrated method.

<Figure 2> is inserted here.

3.1 Construction of a FT diagram

The first step of the hybrid approach is to construct a fault tree addressing the events' interaction resulting in container loss. In the process, the FT is developed with references from containership accidents (which occurred last two decades) databases and investigation reports, as well as previous literature, and with the assistance of a group of marine experts. The experts familiar with containership cargo operations on board are involved as consultants due to the lack of failure probability data in the maritime industry [68]. Failures related to crew performance, environmental factors, technical and mechanical failures, and equipment functions are considered altogether for an effective FTA.

3.2 Data derivation under the IT2FS-SLIM approach

This section presents the data derivation process to evaluate human error contribution to the operational risks. The evaluation of HEPs in the maritime industry is regarded as onerous due to the scarcity of numerical data [68,76]. The IT2FS-based SLIM approach can generate HEPs, particularly in cases where a lack of numerical data exists. In the SLIM, the marine experts provide professional judgement to bridge the gap. Under the hybrid approach, the probabilities for each human error-related basic event are acquired. Accordingly, the main steps of the process and their brief explanations are as follows.

Step 1. PSF derivation: The PSFs which could trigger human errors such as experience, time availability, fatigue, collaboration quality stress, etc. have a considerable effect on ship crew performance and they are acquired by a group of marine experts.

Step 2. PSF rating: Each PSF is rated by the experts after the derivation process. At this step, a value from 1 to 9 on a linear scale is nominated in order of importance on the related basic event. If a factor has a remarkable impact on the crew performance for the relevant event, value '1' is assigned by marine experts.

Step 3. PSF weighting: Each PSF to trigger human error has a relative contribution compared to others. Accordingly, a relative weight will be assigned for each PSF from one expert to the other [57]. In the conventional SLIM, experts subjectively weigh the PSFs. The weighting process is carried out utilising the interval type-2 fuzzy linguistic scale developed by Chen and Lee [43] to enhance the accuracy and reduce the subjectivity of these judgements.

Step 4. SLI Determination: Following the rating and weighting process of PSFs, the SLI value is calculated using the equation (7). The SLI is a crucial tool for predicting the probability of events in which several human errors may occur.

Step 5. HEP derivation: Once the SLI is calculated, it is then possible to obtain the HEP values of each BE in the FT. The conversion of the SLI values to HEP is accomplished by the logarithmic relationship given in equation (8) and is the fundamental aspect of the SLIM technique.

3.3 Computing TE and MCSs failure probabilities

The IT2F-based SLIM approach to performing HEP assessments provides probabilistic outcomes for risk assessment in maritime transportation. The HEPs obtained by utilising the IT2F-SLIM steps are incorporated into the FT of container loss. Based on these outcomes, the failure probability of all BEs is calculated. Thereby, the overall likelihood of the top event (TE) and MCSs are computed for detailed risk analysis.

4. Model application: The case of container loss risk

This paper evaluates the container loss probability in containership cargo operations based on an FTA structure under IT2F-SLIM approach is developed to conduct a comprehensive risk analysis.

4.1 Problem statement

Several factors ranging from rough seas and heavy weather conditions to more catastrophic events such as collision, explosion, grounding, and hull damage can result in containers being lost at sea [75]. Apart from mentioned events, the likelihood of having other major hazard events such as listing, capsizing, structural fracture, and stack collapse leading to container loss is also significant during the cargo operations at the port period. In this study, containership loading operation is selected to illustrate the applicability of the proposed hybrid approach since it has potential risks for the safety of a container ship, its crew and cargo, shore-based workers, port facilities, and the marine environment.

In accordance with non-mandatory and mandatory regulations issued by authorities, to avoid unwanted events, significant items must be checked by the watchkeeping team regularly. Ship stability values (GM, bending moment, torsion moment, drafts, trim, and shearing force), stowage plan, visibility line, specific containers such as IMDG, reefers and, OH/OOG, lashing gear, lashings of containers, and hatch covers demands great attention [77] throughout the containership cargo operation. In this context, crew performance plays a considerable part in risk analysis in identifying what errors lead to or contribute to the top event. However, whilst determining the human error contributions in the shipboard operations the human error should be treated as a combined outcome of some factors onboard the ship. Besides, failure can sometimes be beyond the crew's control, although rare. Shipper-related issues (i.e., mis declared cargo and incorrectly/poor container packing), port-related issues (issues with hoisting cranes and port storage, poorly stacking containers, and poor arrangement of weight distribution), and environmental conditions are also relevant factors in losing containers.

4.2 Analysis of respondents

Accident data sets, investigation reports, and empirical studies are the ideal, and key sources for human error prediction [59]. However, the data on maritime transportation is scarce or incomplete due to commercial reasons [68]. To meet this challenge, the SLIM utilises qualified experts' judgements in the decision-making process to predict human errors. In this study, the appraisal of human error contribution to ship operations is evaluated with the participation of 10 qualified experts with substantial seagoing and working experience in containership transportation. 2 out of these marine experts also have working experience as operation manager in container terminals. The following criteria were determined to form an expert group in this research; i.) Minimum oceangoing Master license, ii.) Minimum ten years of experience onboard container ship, and iii.) Physically participated in cargo handling operation on board container ship. At this point, Table 1 contains the profile details of marine experts. The marine experts make professional judgements expressing the PSFs impacts on each human error-related basic event utilising the linguistic statements of defined type-2 fuzzy sets.

<Table 1> is inserted here

4.3 Data derivation under the IT2FS-SLIM approach

This section summarises how the HEP data is derived to perform quantitative risk analysis. Since the loss of container operational risk is a concern, Table 2 illustrates the fundamental container handling tasks throughout the operation at a container terminal.

<Table 2> is inserted here.

In the study, seven PSFs used are captured from the recent study associated with containership handling operations [38]. Since it has paramount importance to derive appropriate PSFs rather than all PSFs, experience, stress, fatigue, training, time limitation, complexity and safety culture were specified by the Elicitation Review Team (ERT) as effective PSFs on crew performance during the loading operation. A brief description of each PSF included in the HEP assessment is given below, respectively.

- Stress: Negative effect upon seafarer performance to complete the task correctly due to increased anxiety and pressure.
- Experience: Familiarity with the task and knowledge.
- Training: Expansion of knowledge, performance, and capability of seafarers by activities or actions organised by ship management.
- Fatigue: Extreme tiredness caused by mental/physical workload or illness.

• Time Limitation: Amount of time required for the seafarer to complete the relevant task.

• Complexity: The measure of task difficulty identifies interrelated and interdependent task components.

• Safety Culture: Both individual or group perceptions, attitudes and values that reflect ship management's commitment to safety.

The further step is to determine the PSF rating for each task. The PSFs are rated by marine experts due to the lack of failure data in the shipping industry. The marine experts nominated a rate for each determined task according to the 1-9 linear scale, which reflects their relative judgements. The geometric means of ratings of 10 experts participating in the survey were obtained to simplify the calculation. Accordingly, table 3 illustrates PSF rates for each task.

<Table 3> is inserted here.

After having determined PSFs, the weighting process is performed. The IT2Fs are used for the weighting process of PSFs since it is capable of handling inaccurate information in a logically correct manner. In this context, Table 4 demonstrates the IT2FSs number, and their membership functions related to the linguistic terms for determining the PSFs' importance weight [43]. The next step is to calculate the defuzzified values of PSFs weights. In this context, linguistic variables are converted to the IT2FSs to quantitatively transform the judgements of marine experts. Once the average IT2Fs values are calculated, the defuzzification is conducted using equation (1). Table 5 shows IT2FS, crisp and normalised values of PSFs [38].

<Table 4> is inserted here.

<Table 5> is inserted here.

The HEP values are calculated using equations (7 &8) where a and b are the constants. Given the above equations, Table 6 illustrates the SLI values and derived HEP results.

<Table 6> is inserted here.

4.4 Quantitative risk assessment for container loss

This section performs quantitative risk analysis for container loss by systematically predicting human error contributions to the operational risks. To achieve this purpose, the FT is constructed by reviewing accident investigation reports, literature, and marine experts' judgement. In the constructed FTA, 30 basic events that will be effective in the realization of the top event have been determined. At this point, the environmental conditions have been ignored since no environmental obstacle hinders the present real-time containership cargo operation, and the human error contribution was the focal point. Table 7 illustrates the TE, BE and IE for container loss risk in this context.

Three main events cause the top event identified as container loss in the fault tree. These are the failures associated with cargo (IE01), failures associated with lashing (IE02) and failures associated with cargo handling (IE03). Having just one of these three main intermediate events is sufficient to cause container damage. Therefore, IE01, IE02, and IE03 are linked to the TE with the "OR" gate. Accordingly, Figure 3 depicts the FT diagram for container loss during cargo handling operations in maritime transportation.

< Table 7 > is inserted here.

< Figure 3 > is inserted here.

From the FT diagram and logic gates, TE (container loss) occurrence probability was calculated by applying Eqs. (9)– (10), respectively. Based on the results, the occurrence probability of TE is found to be 5.54E-01. Accordingly, the MCSs, their occurrence probabilities, and the V–FIM list of MCSs are depicted in Table 8 (Eqs. (11)– (13)).

< Table 8 > is inserted here.

4.5. Findings and extended discussion

In light of the comprehensive risk assessment for container loss during the loading operation, the top event occurrence probability was calculated as 5.54E-01 which is a rather high. The obtained results show that 55 out of 100 cases may result in container loss due to the paramount contribution of human error during the loading operation. Since the fault tree structure is a graphic model representing the logical interrelationships of basic events, the possibility of each

BE that includes human errors resulting in container loss was calculated to achieve TE occurrence probability. At this point, BE6 (1.38E-01), BE7 (1.20E-01), and BE21 (1.14E-01) with the highest HEP values were found to be the most contributory basic events increasing the risk of TE, respectively.

Further, the occurrence probabilities of the MCSs, the smallest combination of the BEs, were also calculated to identify the structural vulnerability of the system. Based on the results, BE4 (Misdeclaration/under declaration of the actual type/materials of Cargo) and BE5 (Misdeclaration/under declaration of the actual weight of the container) were the basic events that derive the most MCSs (4 MCSs for each) among the others.

Lashing gear is a crucial item that needs to be checked by the watchkeeping team properly. Unlocked hatch cover cleats and loose lashings can cause a container stack to move and force on the adjacent stacks while the vessel is underway. Even worse, the forces on the adjacent stacks shall gradually increase and put the lashing equipment under additional load when the vessel rolls. Accordingly, any failure on lashing gear results in container loss due to stack collapse. However, the increasing effect of factors such as fatigue and limited time, makes the crew more vulnerable to errors, unavoidably.

One of the most significant goals of safe container handling is to minimise the occurrence probability of leaks, spills, or damage. Leakage is a crucial problem in the storage and transport of containers because it may corrode other stacked containers or produce toxic or inflammable fumes if they especially contain dangerous goods. Further, one of the essential parts of the planning is the confirmation that the permissible sequences of masses in stacks are not exceeded. Nevertheless, the weight of the leakage container becomes lighter as time goes by, resulting in container loss due to stack collapse. The primary cause of leakage is rough and inattentive container handling that causes structural damage during cargo operation, in general. Hence, each stowed container should be kept under strict control against any leakage throughout the handling process. At this point, safety culture, fatigue and training were determined as influential factors on human performance in the event of failure.

As for the misdeclared/undeclared cargo, the consequences can be catastrophic in some cases, an example being the disaster that resulted in the loss of the containership ‘Sea Elegance’ in 2003 [9]. The report of the preliminary enquiry revealed that the fire and then explosion onboard originated in a container containing Calcium Hypochlorite that had not been declared [78]. Tragically, the disaster resulted in the death of one crew member and extensive cargo and vessel damage.

The disastrous explosion occurred in a cargo hold of the containership Hanjin Pennsylvania in 2002 [6,8,9] is another unfortunate example of the significance of the subject. The containers filled with fireworks have been mis declared on the manifest. Thereby, the containers listed as having non-hazardous content were incorrectly stacked at the bottom of the hold and did not segregate as appropriate. The ship stayed afloat, but the disaster resulted in the death of two crew members and a substantial loss of cargo.

The consequences of underdeclared weights of containers led to a profound contribution to the catastrophic hull failure of MSC Napoli in 2007 [5,10,11]. Essentially, the vessel encountered rough seas that caused her to pitch heavily when on the passage in the English Channel. Following that, a catastrophic failure was suffered from her hull in the way of her engine room and then broke in two. The report by the MAIB (2008) stated a number of factors that contributed to the hull structure failure including the underdeclared weight of containers. All MSC Napoli's containers were weighed again for investigation when beached in the UK, and the total weight of the 137 containers was 312 tonnes heavier than on the manifest. The load on the hull had increased by whipping effect and her hull already did not have sufficient buckling strength in way of the engine room. Although the detected non-compliance level was not evaluated as high, the report by the MAIB [79] identified it as concerning in the occurrence of this catastrophic event.

5. Conclusion

As a result of container losses from container ships, the maritime industry has taken the issue of safe stowage and securing of containers rather seriously because of the growing global concern over marine disasters. Since the tragic events caused the worst environmental disasters last two decades, the issue of container losses at ships is closely associated with environmental and economic aspects of the maritime transportation industry. At this point, identifying the causes of container losses can provide actionable solutions to reduce losses in future.

Despite the technological improvements, maritime operations remain dangerous for port facilities, vessels, the environment, and human life. Based on this, analysing the operational risk factors, and minimising the threats to an acceptable level is vital to enhance safety. Even though technical and mechanical failures are common causes increasing the risks, human error is found to be the most frequent and significant cause of marine accidents according to the conclusions drawn by the investigation reports.

This paper proposes a hybrid approach incorporating FTA and IT2FS-based SLIM to highlight the overriding importance of human-oriented failures in containership operations. In light of the extended risk analysis on real-time containership loading operation, the occurrence probability of the container loss was found to be 5.54E-01 which is considerably high. In the study, the importance of various factors was also identified as triggering human errors that should be addressed including ineffective safety culture, inadequate experience, fatigue, and limited time. Further, that the proposed approach can effectively be applied to identifying the operational vulnerabilities and critical human errors is concluded.

The fundamental limitation of the research is the scarcity of data. In the framework of the HEP assessment process that should contain both relevant data and real case studies, it is rather difficult to obtain empirical data in the maritime industry. Nevertheless, real data should be captured to validate the acquired results. A set of numerical simulations may also be carried out via risk analysis software in potential future research. This study is expected to provide qualitative and quantitative data on container transportation safety and insight into what measures may be necessary to decrease future losses by quantifying the potential failures in loading operations.

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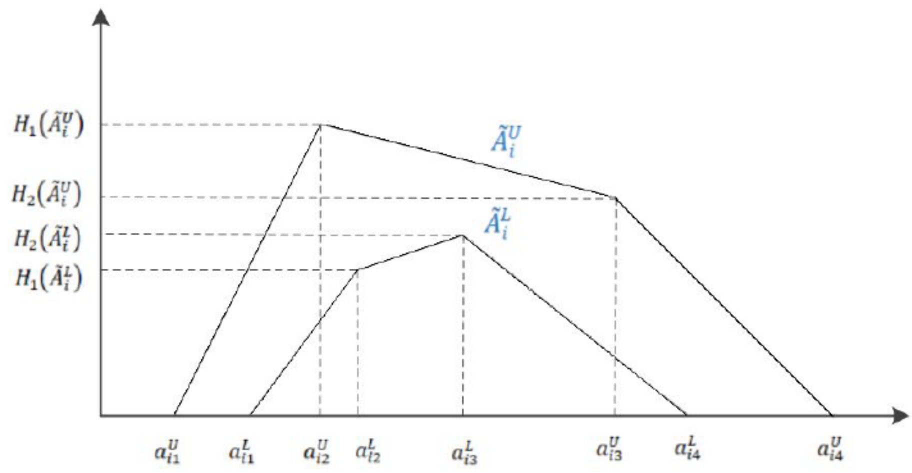
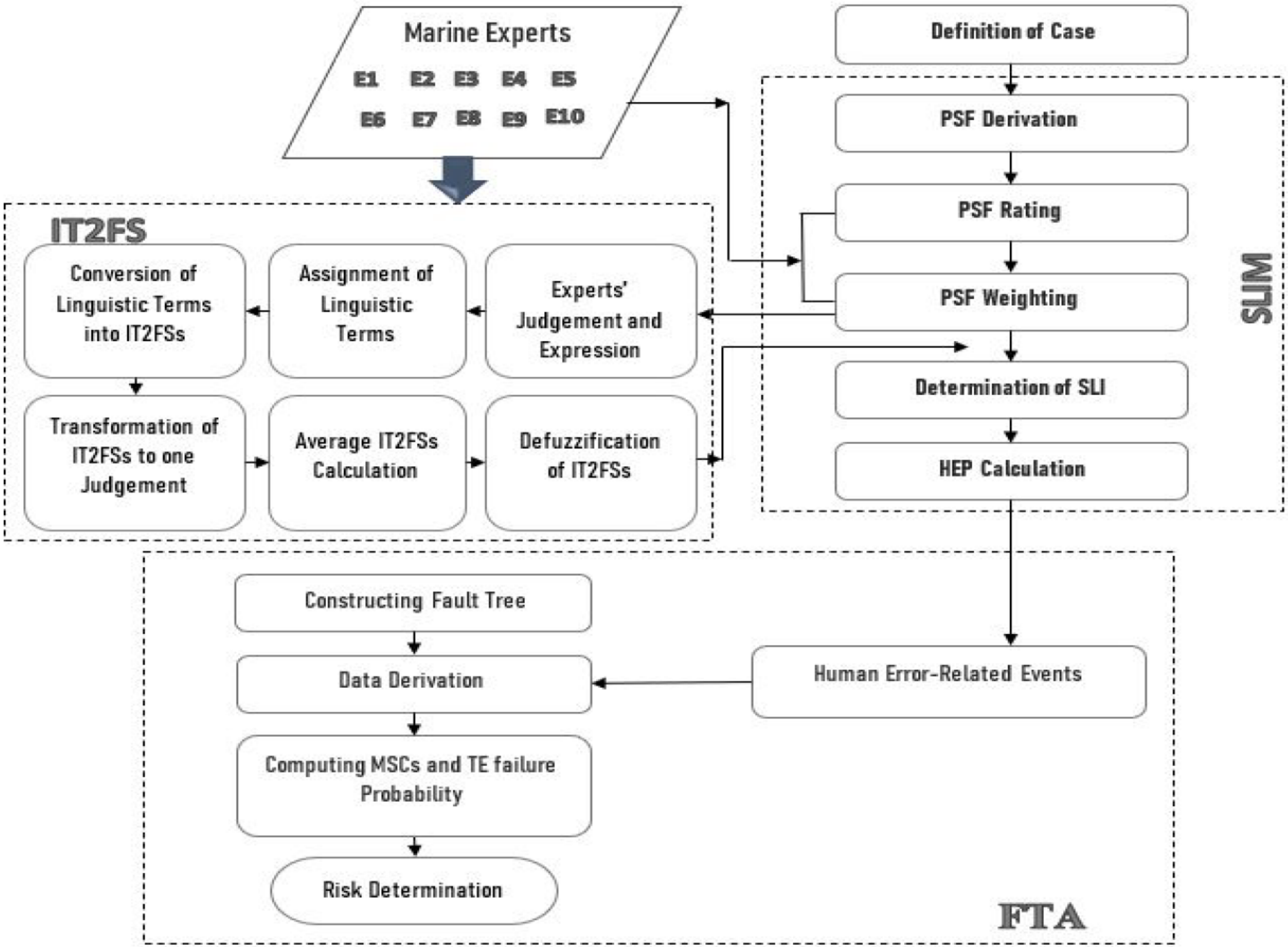
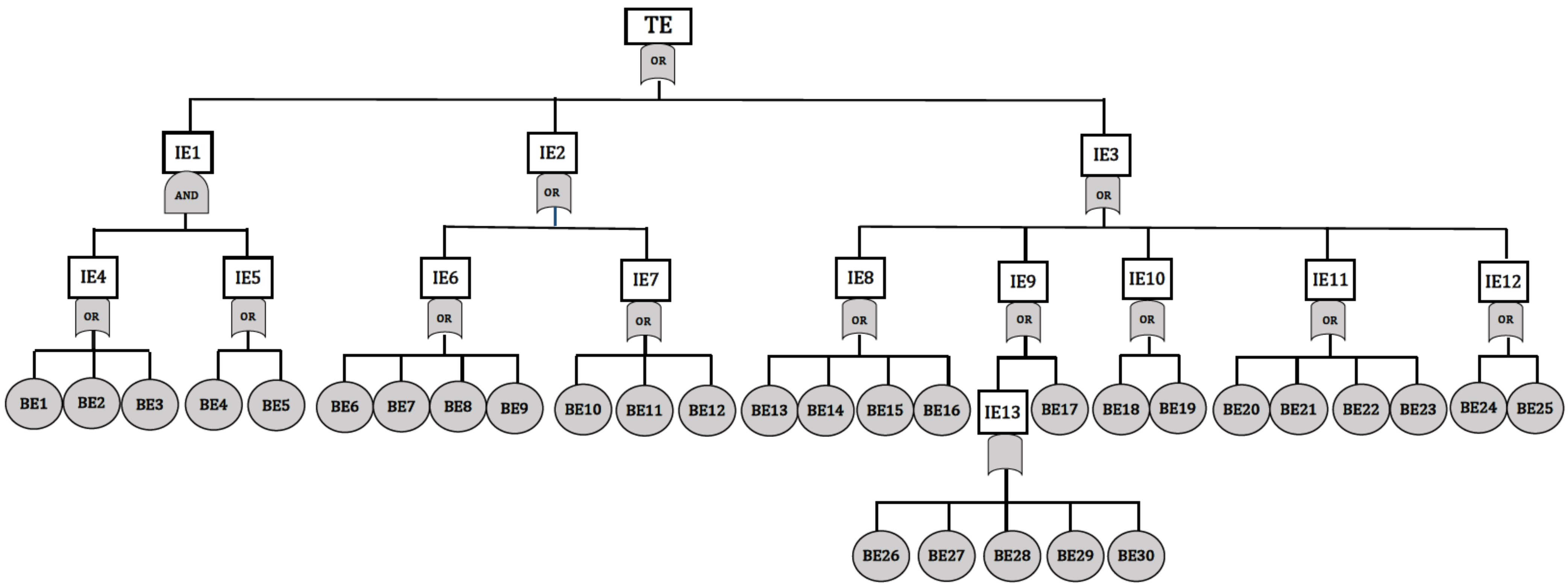
<Figure 1. The trapezoidal membership function of IT2FS>




Marine Experts
E1 E2 E3 E4 E5
E6 E7 E8 E9 E10
IT2FS
Conversion of Linguistic Terms into IT2FSs
Assignment of Linguistic Terms
Experts' Judgement and Expression
Transformation of IT2FSs to one Judgement
Average IT2FSs Calculation
Defuzzification of IT2FSs
Definition of Case
PSF Derivation
PSF Rating
PSF Weighting
Determination of SLI
HEP Calculation
SLIM
Constructing Fault Tree
Data Derivation
Computing MSCs and TE failure Probability
Risk Determination
Human Error-Related Events
FTA

<Fig.3 Structure of fault tree for the loss of container at port>



<Table 1. Marine experts' profile details>

Marine Expert ID	Age	Company	Position	Experience (as year)
1	43	Company A	Opr. Manager	14
2	48	Company B	Oceangoing Master	15
3	43	Company C	Oceangoing Master	10
4	41	Company B	Oceangoing Master	18
5	44	Company B	Oceangoing Master	13
6	64	Company C	Oceangoing Master	25
7	43	Company C	Oceangoing Master	22
8	36	Company D	CFS Opr. Manager	10
9	35	Company C	Oceangoing Master	11
10	40	Company C	Oceangoing Master	16

<Table 2. Task analysis for container handling operation >

Task	Description of Task
1	Equally distributing of weight inside the container
2	Stacking of goods inside the container against to move
3	Properly packing of goods inside container against to degradation/chemical reaction
4	Accurately declaring the type/material of good
5	Accurately declaring the container's weight
6	Tightening/re-tightening loose lashing gear (lashing bars, turnbuckles)
7	Locking the cleats on all sides of all hatch covers
8	Locking all twist locks as appropriate against to move
9	Adhering to the recommended lashing forces
10	Maintaining of the deck fittings (fixed socket, lashing plate, cell guide) against the forces imposed by containers
11	Keeping all lashing equipment (twist lock, cone, bar) qualified and ready for use
12	Selecting the lashing gear compatible with fixed deck fitting
13	Well operating of gantry/mobile crane
14	Container handling by a trained crane operator
15	Port adequateness and opportunities for loading (lights, breakwater, capability..etc)
16	Being aware of the wind forces throughout operation
17	Preparing of the stowage plan in accordance with the requirements of codes
18	Maintaining proper communication as to the operational process
19	Maintaining proper communication between ship crew and responsible shore personnel
20	Container handling by spreader consisting of a steel frame and four hooks
21	Frequently checking of the stacked containers against leakage
22	Loading of the special-type container in accordance with the requirements
23	Checking of coupled lashing equipment sufficiency against being missing
24	Timely changing in ballast as to the ship's condition
25	Properly activating/deactivating of heeling/ballast system
26	Frequently checking the visibility line and/or steering light sight
27	Adhering to the permissible stack weight
28	Adhering to partial loading quantity
29	Adhering to max GM and stress values
30	Adhering to permissible sequences of masses in stacks

<Table 3. Geometric means of PSF ratings based on the marine experts' evaluations >

Task	*Performance Shaping Factor*						
	Stress	Experience	Training	Fatigue	Time Lim.	Complexity	Safety Culture
1.	7	3	4	4	2	4	3
2.	7	2	4	4	2	5	3
3.	7	2	3	5	2	4	3
4.	6	2	4	5	4	5	3
5.	5	3	3	6	4	5	2
6.	5	2	3	3	2	3	3
7.	4	3	3	2	3	4	2
8.	4	3	4	3	2	4	2
9.	7	2	3	5	3	4	3
10.	7	2	4	3	3	6	3
11.	5	4	4	3	3	4	3
12.	7	3	4	5	4	4	5
13.	6	3	3	4	2	3	3
14.	5	2	3	3	3	5	4
15.	6	3	4	5	4	4	4
16.	6	2	3	5	4	5	3
17.	5	2	2	3	3	3	3
18.	6	3	3	3	2	5	3
19.	7	3	4	4	2	5	4
20.	4	3	3	3	3	3	2
21.	4	2	3	3	3	4	2
22.	6	3	3	4	4	3	3
23.	3	3	4	3	2	4	2
24.	5	2	3	4	3	4	4
25.	5	2	3	5	3	3	3
26.	4	3	3	3	3	3	2
27.	7	2	3	5	4	4	3
28.	7	2	3	5	3	3	3
29.	6	2	3	5	3	3	3
30.	6	3	4	4	3	3	3

Table 4: Lingusitic terms and their corresponding IT2FSs

Linguistic Assessment	Term	Interval Type 2 Fuzzy Sets
Very Low	VL	((0.0;0.0;0.0;0.1;1.0;1.0) , (0.0;0.0;0.0;0.05;0.9;0.9))
Low	L	((0.0;0.1;0.1;0.3;1.0;1.0) , (0.05;0.1;0.1;0.2;0.9;0.9))
Medium Low	ML	((0.1;0.3;0.3;0.5;1.0;1.0) , (0.2;0.3;0.3;0.4;0.9;0.9))
Medium	M	((0.3;0.5;0.5;0.7;1.0;1.0) , (0.4;0.5;0.5;0.6;0.9;0.9))
Medium High	MH	((0.5;0.7;0.7;0.9;1.0;1.0) , (0.6;0.7;0.7;0.8;0.9;0.9))
High	H	((0.7;0.9;0.9;1.0;1.0;1.0) , (0.8;0.9;0.9;0.95;0.9;0.9))
Very High	VH	((0.9;1.0;1.0;1.0;1.0;1.0) , (0.95;1.0;1.0;1.0;0.9;0.9))

<Table 5. Calculated average IT2F values >

PSF	IT2FSs	Crisp Value	Normalised Value
Stress	((0.36;0.55;0.55;0.73;1;1) , (0.46;0.55;0.55;0.64;0.9;0.9))	0.604	0.107
Experience	((0.76;0.92;0.92;0.99;1;1) , (0.84;0.92;0.92;0.96;0.9;0.9))	0.929	0.165
Training	((0.42;0.62;0.62;0.8;1;1) , (0.52;0.62;0.62;0.71;0.9;0.9))	0.673	0.119
Fatigue	((0.76;0.92;0.92;0.99;1;1) , (0.84;0.92;0.92;0.96;0.9;0.9))	0.929	0.165
Time Lim.	((0.72;0.88;0.88;0.96;1;1) , (0.8;0.88;0.88;0.92;0.9;0.9))	0.893	0.158
Complexity	((0.38;0.58;0.58;0.77;1;1) , (0.48;0.58;0.58;0.68;0.9;0.9))	0.637	0.114
Safety Culture	((0.82;0.96;0.96;1;1;1) , (0.89;0.96;0.96;0.98;0.9;0.9))	0.957	0.171

<Table 6. Calculated HEP values for cargo handling operation >

Task	Calculated SLI	*Log -HEP*	HEP
1.	3.73	-3.35	4,48E-04
2.	3.75	-3.41	3,86E-04
3.	3.51	-2.73	1,85E-03
4.	3.99	-4.06	8,61E-05
5.	3.89	-3.78	1,65E-04
6.	2.84	-0.86	1,38E-01
7.	2.86	-0.92	1,20E-01
8.	2.95	-1.17	6,72E-02
9.	3.49	-2.68	2,09E-03
10.	3.78	-3.47	3,38E-04
11.	3.76	-3.43	3,70E-04
12.	4.34	-5.04	9,12E-06
13.	3.44	-2.53	2,92E-03
14.	3.40	-2.41	3,87E-03
15.	4.24	-4.77	1,71E-05
16.	3.75	-3.40	3,97E-04
17.	2.88	-0.96	1,09E-01
18.	3.40	-2.41	3,91E-03
19.	3.84	-3.64	2,27E-04
20.	3.04	-1.40	3,95E-02
21.	2.87	-0.94	1,14E-01
22.	3.46	-2.59	2,58E-03
23.	2.87	-0.95	1,13E-01
24.	3.40	-2.42	3,83E-03
25.	3.41	-2.45	3,52E-03
26.	3.04	-1.43	3,76E-02
27.	3.74	-3.37	4,22E-04
28.	3.58	-2.92	1,21E-03
29.	3.50	-2.71	1,94E-03
30.	3.58	-2.92	1,19E-03

<Table 7. Fault tree events for the loss of containers >

Event	Description
TE	Container loss
IE1	Failures associated with cargo
IE2	Failures associated with lashing
IE3	Failures associated with cargo handling
IE4	Packing failure
IE5	Misinformation
IE6	Lashing plan (comply with CSM) violation
IE7	Deck-fitting and lashing equipment failure
IE8	Terminal-induced handling failures
IE9	Stowage plan failure
IE10	Communication failure
IE11	Improper handling
IE12	Improper ballast operation
IE13	Stowage plan application failure
BE1	Incorrect weight distribution
BE2	Mobility due to poor stack
BE3	Inaccurate packing
BE4	Misdeclaration/under declaration of the actual type/materials of cargo
BE5	Misdeclaration/under declaration of the actual weight of the container
BE6	Loose lashing gear (lashing bars and turnbuckles)
BE7	Unlocked hatch cleats
BE8	Unlocked twist locks
BE9	Exceeding the recommended lashing forces
BE10	Deck fittings failure
BE11	Broken/bent equipment (twist locks, turnbuckles, bars, etc.)
BE12	Improper equipment for fixed deck fittings
BE13	Gantry/Mobile crane failure
BE14	Operator handling failure
BE15	Port restrictions
BE16	Lack of awareness for wind effect
BE17	Inadequate planning
BE18	Miscommunication as to the operation's actual process
BE19	Lack of communication between crew and stevedore/foreman
BE20	Hook Spreader Usage
BE21	Leakage container loading
BE22	Incorrect special-type container loading
BE23	Missing equipment
BE24	Ballast change failure
BE25	Heeling/ballast system failure
BE26	Exceeding the max. number of containers in each stack
BE27	Exceeding permissible stack weight
BE28	Extreme partial loading
BE29	Exceeding the max GM and stress values
BE30	Neglecting permissible sequences of masses in stacks

< **Table 8**. Ranking of basic events according to Fussel-Vessely importance>

Basic Events	Failure Probability of BEs	Number of MCS	MCS Elements	FV-I	Ranking
BE1	4,48E-04	3	BE1, BE1BE4, BE1BE5	4.48E-04	20
BE2	3,86E-04	3	BE2, BE2BE4, BE2BE5	3.86E-04	23
BE3	1,85E-03	3	BE3, BE3BE4, BE3BE5	1.85E-03	17
BE4	8,61E-05	4	BE4, BE1BE4, BE2BE4, BE3BE4	8.65E-05	28
BE5	1,65E-04	4	BE5, BE1BE5, BE2BE5, BE3BE5	1.65E-04	27
BE6	1,38E-01	1	BE6	1.38E-01	1
BE7	1,20E-01	1	BE7	1.20E-01	2
BE8	6,72E-02	1	BE8	6.72E-02	6
BE9	2,09E-03	1	BE9	2.09E-03	15
BE10	3,38E-04	1	BE10	3.38E-04	25
BE11	3,70E-04	1	BE11	3.70E-04	24
BE12	9,12E-06	1	BE12	9.12E-06	30
BE13	2,92E-03	1	BE13	2.92E-03	13
BE14	3,87E-03	1	BE14	3.87E-03	10
BE15	1,71E-05	1	BE15	1.71E-05	29
BE16	3,97E-04	1	BE16	3.97E-04	22
BE17	1,09E-01	1	BE17	1.09E-01	5
BE18	3,91E-03	1	BE18	3.91E-03	9
BE19	2,27E-04	1	BE19	2.27E-04	26
BE20	3,95E-02	1	BE20	3.95E-02	7
BE21	1,14E-01	1	BE21	1.14E-01	3
BE22	2,58E-03	1	BE22	2.58E-03	14
BE23	1,13E-01	1	BE23	1.13E-01	4
BE24	3,83E-03	1	BE24	3.83E-03	11
BE25	3,52E-03	1	BE25	3.52E-03	12
BE26	3,76E-02	1	BE26	3.76E-02	8
BE27	4,22E-04	1	BE27	4.22E-04	21
BE28	1,21E-03	1	BE28	1.21E-03	18
BE29	1,94E-03	1	BE29	1.94E-03	16
BE30	1,19E-03	1	BE30	1.19E-03	19

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: