Journal of *Marine Science and Engineering*

MDPI

Article

Identifying the Most Probable Human Errors Influencing Maritime Safety

Xiaofei Ma [1,2], Guoyou Shi [1,2,*], Weifeng Li [1,2] and Jiahui Shi [1,2]

[1] Navigation College, Dalian Maritime University, Dalian 116026, China
[2] Key Laboratory of Navigation Safety Guarantee of Liaoning Province, Dalian 116026, China
* Correspondence: sgydmu@163.com

Abstract: In the traditional and extended shipboard operation human reliability analysis (SOHRA) model, the error-producing condition (EPC) is critical. The weight and proportion of each EPC in one specific task are often determined by the experts' judgments, including most of the modified versions. Due to this subjectivity, the result and recommended safety measures may not be as accurate as they should be. This study attempts to narrow the gap by proposing a novel approach, a combination of SOHRA, entropy weight method, and the TOPSIS model. The entropy weight and TOPSIS method are employed to decide the weight of each EPC based on the foundation of the SOHRA model. A cargo-loading operation from a container ship is analyzed to verify this model. The results suggest that the entropy-weighted TOPSIS method can effectively determine the weights of EPCs, and the eight most probable human errors are identified.

Keywords: human error; loading operation; ship safety; shipboard operation human reliability analysis; entropy-weighted TOPSIS method

Citation: Ma, X.; Shi, G.; Li, W.; Shi, J. Identifying the Most Probable Human Errors Influencing Maritime Safety. *J. Mar. Sci. Eng.* **2023**, *11*, 14. https://doi.org/10.3390/jmse11010014

Academic Editors: Marko Perkovic, Lucjan Gucma and Sebastian Feuerstack

Received: 13 November 2022
Revised: 9 December 2022
Accepted: 16 December 2022
Published: 22 December 2022

1. Introduction

Human error is a hot research topic in the aviation, nuclear energy, healthy service, railway, and maritime fields. This is because many related accidents or incidents have connections with human errors [1–3]. For example, studies [4–6] show that around 80% of maritime accidents are caused by human error, or at least have a connection with human error. Furthermore, human error can cause significant accidents, thus inducing substantial economic losses, environmental pollution, or even human life losses.

As the central part of human factor research, the study of human error can be traced back to the 1930s [7,8]. However, human error, as a trouble-free identified factor, is easy to analyze qualitatively but difficult to study quantitatively. Early on, most of the research did not originate from the maritime field but from aviation [9], nuclear energy [10], railway [11,12], factory [13,14], medical care [15,16], other shoreside safety management [17], etc. Some methods have already been modified to study maritime safety. Meanwhile, the scanty human error data hampered the relevant research [18], especially in the maritime domain. Therefore, some alternative methods, such as human error probability (HEP) [1,19] and human reliability analysis (HRA) [20–22], were developed to obtain human error information more accurately and even predict human error occurrence.

1.1. Human-Error-Related Risk Assessment

Human-error-related risk assessment aims to assess the risk of human error, in other words, to obtain the HEP. According to the values of HEP, the author can assess the human error risks of a specific task. Therefore, HEP is the critical factor utilized in the risk assessment of human error [23].

One frequently used method is the Human Error Assessment and Reduction Technique (HEART), proposed by Williams [24]. Two related factors, human error probability (HEP) and general error probability (GEP), were introduced to assess the risks of human error. The experts' judgments are an essential step in this method. Over time, the model has been modified many times, and its application has been broadened to other fields, e.g., medical care, the chemical industry, road traffic, maritime traffic, etc. Akyuz et al. [25] presented a modified model, incorporating the Analytic Hierarchy Process (AHP) and HEART method, to explore human errors in the tank-cleaning process onboard chemical tankers. The experts' judgments determined the GEPs and EPCs. Although the AHP method is used to weigh the proportion of each EPC, creating a judgment matrix using experts' judgments is still a crucial step in the AHP method. One year later, they [26] proposed another version by combining HEART and interval type-2 fuzzy sets (IT2FSs). The IT2FSs are used to cope with the linguistic variables judged by the experts. Wang et al. [27] utilized an H-HEART-F approach to assessing the HEP of the task. The Z-numbers and decision-making trial and evaluation laboratory (DEMATEL) method are used to address the experts' judgments and the interdependence of each EPC. They are only used to deal with the fuzziness of experts' judgments; the subjectivity of the research method still exists.

Another common model is the Successive Likelihood Index Method (SLIM) developed by Embrey et al. [28]. It is used to assess the HEP so that mitigation measures can be adopted to minimize human error, especially when scanty human error information is available. Islam et al. [29] studied human failure concerning the maintenance procedures of the ship's main engine through the SLIM model. The experts needed to rate the PSFs of each step and weigh those PSFs to obtain an SLI for each sub-task of the process. Akyuz [2] proposed a fuzzy-based SLIM model to explore the human error quantification in abandoned ship operations. Experts' judgments decided the weights of PSFs in the operations. The fuzzy sets were used to process the subjectivity of the experts' judgments, which could mitigate the subjectivity of the process. Erdem et al. [1] presented a modified SLIM model: IT2FS-SLIM. The IT2FS is used to cope with the subjectivity of the experts' judgments so that the sensitivity of the judgments can be mitigated. Islam et al. [23] developed a monograph to assess human error likelihood for maritime operations through the SLIM model; a series of experts' judgments are applied to rate and weight the PSFs according to the steps of the tasks.

Limited by the scanty information on human error, most research has relied on the experts' judgments, including the rating process and weight determination of related factors. The experts' judgments have significant influence on the sensitivity of the results. Some attempts have been applied to mitigate the subjectivity, but, presently, no alternative methods have been found to replace the experts' judgments. Consequently, subjectivity still exists in this research domain.

1.2. Human Reliability Analysis

It is considered that minimizing human error increases human reliability. Therefore, articles focusing on the HRA are considered human-error-related studies. These articles have made an extensive exploration of human error and reduction strategies.

Hollnagel [30] proposed the Cognitive Reliability and Error Analysis Method (CREAM) model to quantify human error retrospectively and prospectively. Because of its ability for quantification, numerous modified versions have been developed to deal with human error in specific operations. Ung [18] used fault tree analysis, fuzzy Bayesian network, and the CREAM method to study human failure in an oil tanker collision situation. The experts' judgments were used to decide the weights and quantitative effects caused by the ambient factors. The factors with the higher occurrence rate were identified. Akyuz [31] modified the CREAM model to analyze human errors when operating the inerting gas operation in an LPG tanker. The evaluations of common performance conditions (CPCs) were performed by the experts, and the relevant judgments were assigned for each primary process. The sub-tasks with higher HEP were identified and the risk mitigation measures were given. By integrating the CREAM model, the Bayesian network, and evidential reasoning, Yang et al. [32] provided a hybrid strategy. The nine CPCs' interaction was considered in the method, which is viewed as its main evolution. Zhou et al. [33], Xi et al. [3], Shirali et al. [34], and Wu et al. [35] also provide improved approaches to studying HRA quantitatively; experts evaluate all the CPCs in these methods.

In addition, Li et al. [36] proposed an Association Rule Bayesian Networks (ARBN) model to study the external factors influencing human error by analyzing ship collision reports. Two separate Bayesian networks, environment–human BN and ship–human BN, were built to evaluate the human error probability better. The experts' judgment was still an unavoidable step for this method.

Swain et al. [37] proposed the Technique for Human Error Rate Prediction (THERP) model around 30 years ago for nuclear power plant applications. It was utilized to predict human error by calculating the HEP values. Now, the model has been successfully adopted in the maritime field. Zhang et al. [38] presented a modified model, THERP-BN, to evaluate the HEP of emergency operations on an autonomous ship. Based on the experts' judgments, the fuzzy number synthesis method was used to obtain the experts' scores so that the HEP could be calculated. The results provided a good reference for constructing a shore control center. Its main improvement was to make complicated things clear and easy to analyze.

There are more models and methods to explore human errors, such as Human Entropy (HENT) [39], BN-HRA [40], Railway Action Reliability Assessment (RARA) [11], Controller Action Reliability Assessment (CARA) [14], Nuclear Action Reliability Assessment (NARA) [15], and A Technique for Human Error Analysis (ATHENA) [41]. Among the existing models, including modified, revised, and hybrid approaches, only marine maintenance and operations human reliability analysis (MMOHRA), SOHRA, HEART, NARA, CARA, and RARA involve EPC calculation. Few of them could obtain the weight of each EPC without the experts' judgment. This article will attempt to narrow this gap. Of the six identified methods, MMOHRA and SOHRA were explicitly developed for the maritime domain; the other four models were not. The MMOHRA model was proposed based on the framework of the SOHRA method. It is more specific than the SOHRA model because it was created exclusively for marine operations and maintenance. Considering that this research will not use marine maintenance operations for verification, the SOHRA model is preferred for this article.

2. Methodology

This study intends to apply the SOHRA model as the foundation for human error probability evaluation. The entropy weight and Technique of Preference by Similarity to Ideal Solution (TOPSIS) method are combined to obtain the weights of EPCs, in other words, to provide the values of the A_i in Equation (1).

2.1. SOHRA Model

In the maritime domain, quantifying human error is demanding since scanty human error data affect its process. Therefore, adopting empirical techniques such as SOHRA to quantify human error probability is practical. SOHRA, a model modified from HEART, is utilized to study human reliability for shipboard activities. The two main characteristics of SOHRA are generic error probability (GEP) and m-EPC. The GEP derived from the HEART model includes nine different values. Each value corresponds to a generic task type (GTT) (from A to M); GTT and GEP can be seen in Akyuz et al. [42]. The m-EPCs [6], derived from EPCs in the HEART model, are special to maritime operations. They are critical factors, internal or external, which could affect people's performance onboard. Furthermore, because its values are obtained based on numerous maritime accident reports, it is applicable for all shipboard operations, including deck work and engine room work. However, for more accurate calculation purposes, improvement of the existing m-EPCs may be required, such as the mmo-EPCs proposed by Kandemir et al. [4].

Here, the EPC values were collected from six different models: MMOHRA, SOHRA, HEART, NARA, CARA, and RARA. Their values can be found in Kandemir et al. [4]. The six models' EPCs may have different names, such as m-EPCs or mmo-EPCs. Whether they are referred to as EPCs, m-EPCs, or mmo-EPCs, we use EPC here for standardization.

The purpose of the SOHRA model is to calculate the HEP value for specific operations, figure out the steps with higher HEP values, and thus give measures or recommendations to manage human errors. Therefore, the HEP values are calculated by Equation (1) as per the SOHRA model.

$$HEP_j = GEP_j \times \left\{ \prod_i [(mEPC_i - 1)A_i + 1] \right\}, i = 1, 2, \cdots, n; j = 1, 2, \cdots, 9 \tag{1}$$

where i represents the number of m-EPCs in each step of the task, j is the number of GEPs, and A_i is the weight of each m-EPC.

Several steps should be implemented to perform this calculation:

Firstly, the task should be identified, and the steps or sub-tasks should be determined as per the hierarchical task analysis (HTA).

Secondly, based on the steps or sub-tasks, a set of scenarios are defined to match the GTT and m-EPC parameters, which include internal and external conditions.

Thirdly, by applying the majority rule, the experts' judgments can help assign the sub-tasks with appropriate GTT and suitable EPCs. Then, the GEP values can be obtained according to the identified GTT, and the EPC values can be obtained from Kandemir et al. [4]. The EPC value "NA" in NARA, CARA, and RARA models is deemed zero for better calculation. Study [6] shows that the values of EPCs positively correlates with human error. A larger value implies a higher probability of human error. If the EPC's value is less than 1, it indicates the EPC has no connection with human error. Therefore, it is reasonable to replace "NA" with zero.

Fourthly, the entropy weight method and TOPSIS approach are used to determine the values of A_i; details are listed in Section 2.2.

Fifthly, the HEP value can be calculated through Equation (1).

The last step is the recommendation of safety barriers to minimize human error, according to the calculated HEP values.

2.2. Entropy Weight Method and TOPSIS Model

The entropy weight method, first developed by Shannon [43], is utilized to obtain the weights of the targets based on the index variability. It has a certain accuracy as an objective method to determine the weight, compared with subjective methods such as AHP. It replaces the expert weight and reduces subjectivity. Furthermore, the weights determined by this method can be modified because of its high adaptability.

Hwang et al. [44] proposed the TOPSIS model to cope with the multi-criteria decision making (MCDM) problem. The blending of the two approaches could minimize the subjectivity of data weighting and is thus suitable for systematic risk and safety assessment [45]. The blended approach based on the two methods can be achieved by implementing the following steps:

Step 1: Based on Table 1, the decision matrix can be obtained.

$$D = \begin{bmatrix} d_{11} & \cdots & d_{1n} \\ \vdots & \ddots & \vdots \\ d_{m1} & \cdots & d_{mn} \end{bmatrix} \tag{2}$$

where d_{mn} is the value of the n-th EPC against the m-th approach. m represents the number of approaches; n means the total number of EPCs in Table 1. The calculation will be performed when m = 3 (the first three approaches) and m = 6 (all approaches). Table 2 shows the simple notation of EPCs and approaches.

Table 1. Task description of a cargo-loading operation.

Sub-Task Description of Task	
1. Human Safety	
1.1	Make sure that all crew on deck use PPE
1.2	Use safety belt when working/climbing on containers
1.3	Keep clear from the container passage area
1.4	Be aware of the risks of mislaid equipment on operated container
1.5	Be aware of the risks of lashing operations on bays at which cargo operations are occurring
2. Ship/Cargo Security	
2.1	Check if any oil is dropped off from gantry to the deck
2.2	Check all cellguides against any damage during operation
2.3	Check the seal of loading containers
2.4	Check if the top cover of OT container is damaged and not preventing another container being put on them
2.5	Check the IMO signs/labels of dangerous cargoes
2.6	Check the tightness of all straps on flatrack containers if any
2.7	Make sure that on/off switch is kept off before connection of reefer plug
2.8	Check the temperature setting degree and ventilation and humidity settings (%) of reefer container
2.9	Consider the height while loading HC/OT containers in hold
2.10	Inform C/O in case flatrack container is overhighed or overgauged than declared
2.11	Check if loading containers in balance on port/starboard side of the ship
2.12	Inform the office-charterer-agent if the ship heels more than 5° during loading
2.13	Inform C/O if hook spreaders are used for cargo operations
2.14	Check if the leakage containers onboard
2.15	Inform C/O in case damaged container is observed
2.16	Prepare interchange report for damaged containers
2.17	Inform the charterer and management office if the container is heavily damaged
2.18	Check the ship's ropes during operation frequently
2.19	Keep the drafts under strict control during cargo operation

Table 2. Simple notation of EPCs and Approaches.

EPCs	Series No.	EPCs	Series No.	EPCs	Series No.	Approaches	Series No.
EPC1	S1	EPC14	S14	EPC27	S27	MMOHRA	T1
EPC2	S2	EPC15	S15	EPC28	S28	SOHRA	T2
EPC3	S3	EPC16	S16	EPC29	S29	HEART	T3
EPC4	S4	EPC17	S17	EPC30	S30	NARA	T4
EPC5	S5	EPC18	S18	EPC31	S31	CARA	T5
EPC6	S6	EPC19	S19	EPC32	S32	RARA	T6
EPC7	S7	EPC20	S20	EPC33	S33	-	-
EPC8	S8	EPC21	S21	EPC34	S34	-	-
EPC9	S9	EPC22	S22	EPC35	S35	-	-
EPC10	S10	EPC23	S23	EPC36	S36	-	-
EPC11	S11	EPC24	S24	EPC37	S37	-	-
EPC12	S12	EPC25	S25	EPC38	S38	-	-
EPC13	S13	EPC26	S26	-	-	-	-

Step 2: the values in the decision matrix are normalized with the following equations to avoid the dimension differences of various factors:

$$d_{ij}^{'} = \frac{d_{ij} - \overline{d_i}}{s_j}, i = 1, 2, \cdots, m; j = 1, 2, \cdots, n \quad (3)$$

$$\overline{d_i} = \frac{1}{n} \sum\nolimits_{i=1}^{n} d_{ij} \quad (4)$$

$$s_j = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(d_{ij} - \overline{d_i}\right)^2}, j = 1, 2, \cdots, m \tag{5}$$

Since the values of d'_{ij} should be positive, there is no indication that they are necessarily positive after processing. Therefore, a transformation should be performed to make them positive:

$$d_{ij} = d'_{ij} + b \tag{6}$$

where b is the minimum value that could ensure all the d'_{ij} are positive.

$$f_{ij} = \frac{d_{ij}}{\sum_{j=1}^{n} d_{ij}}, i = 1, 2, \cdots, m; j = 1, 2, \cdots, n \tag{7}$$

where f_{ij} is the decision matrix after standardization.

Step 3: The information entropy can be calculated according to the final decision matrix and entropy theory:

$$E_j = -\frac{1}{\ln n}\sum_{j=1}^{n} f_{ij} \ln f_{ij}, i = 1, 2, \cdots, m \tag{8}$$

If $f_{ij} = 0$, define $f_{ij} \ln f_{ij} = 0$.

Step 4: Then the entropy weight of all the elements can be obtained:

$$w_i = \frac{1 - E_i}{\sum_{i=1}^{m}(1 - E_i)}, i = 1, 2, \cdots, m \tag{9}$$

Step 5: Based on the standardized decision matrix and the entropy weights, the weighted normalization matrix can be calculated using Equation (10):

$$\mathrm{P} = \left(p_{ij}\right)_{m\times n} = w_i \times f_{ij} = \begin{bmatrix} w_1 f_{11} & w_1 f_{12} & \cdots & w_1 f_{1n} \\ w_2 f_{21} & w_2 f_{22} & \cdots & w_2 f_{2n} \\ \vdots & \vdots & & \vdots \\ w_m f_{m1} & w_m f_{m2} & \vdots & w_m f_{mn} \end{bmatrix}, i = 1, 2, \cdots, m; j = 1, 2, \cdots, n \tag{10}$$

Step 6: The positive ideal solution Q^+ and the negative ideal solution Q^- are easy to obtain according to the TOPSIS approach:

$$\text{Positive ideal solution}: \ Q^+ = \left[\left(\max p_{ij}/i\right)\right] = \left[q_1^+, q_2^+, \cdots, q_m^+\right] \tag{11}$$

$$\text{Negative ideal solution}: Q^- = \left[\left(\min p_{ij}/i\right)\right] = \left[q_1^-, q_2^-, \cdots, q_m^-\right] \tag{12}$$

Step 7: The relative distances between the p_{ij} and the positive ideal solution (PIS) and negative ideal solution (NIS) are as follows:, respectively,

$$R_j^+ = \sqrt{\sum_{i=1}^{m}\left(p_{ij} - q_i^+\right)^2}, j = 1, 2, \cdots, n \tag{13}$$

$$R_j^- = \sqrt{\sum_{i=1}^{m}\left(p_{ij} - q_i^-\right)^2}, j = 1, 2, \cdots, n \tag{14}$$

Step 8: The final results are the relative closeness of the factors to the positive ideal solution and negative ideal solution:

$$A_j = \frac{R_j^-}{\left(R_j^- + R_j^+\right)}, j = 1, 2, \cdots, n \tag{15}$$

The evaluation value A_j represents the degree of correlation between EPCs and HEP. Its range is from 0 to 1. A large value of A_j means a greater relevance of the two elements and vice versa.

3. Case Study and Results

To verify the proposed approach, a cargo loading operation from a container ship was applied to demonstrate its effectiveness. Cargo loading is one of the critical operations onboard, involving a series of tasks including shipboard cooperation and ship-shore co-operation. The potential risks include crew members' safety, shoreside workers' safety, cargo condition, ship equipment, port facilities, environment damage, etc. These risks correlate well with human activities, and thus are suitable for analyzing human failures and developing corresponding safety barriers to minimize the potential risks.

The identified cargo loading process comes from Erdem et al. [1]. The task descriptions are listed in Table 1. The calculations were performed according to the statement in Sections 2.1 and 2.2. Seven masters were invited as experts for this research, and their information is listed in Table 3. The results are given in this section after elaborating on the calculation process. Based on the experts' judgments, the sub-tasks were assigned to their related GTT and corresponding m-EPCs (Table 4). Figure 1 shows the calculation results of A_{s1} and A_{s2}. S_1 represents scenario 1, S_2 represents scenario 2, and R means the reference data, where A_{s1} is the result of the first scenario (only T1, T2, and T3 models are involved) and A_{s2} is the result of the second scenario (T1, T2, T3, T4, T5, and T6 models are involved). The results indicate that significant differences exist between the two scenarios. The final results will tell which scenario is better. Then, the calculated HEPs were obtained separately, based on the two scenarios, and a comparison is illustrated in Table 5. The reference data are from Erdem et al. [1].

Table 3. Experts' profiles.

Expert No.	1	2	3	4	5	6	7
Rank onboard	master	master	master	master	master	master	master
Sea age	15	21	17	29	32	24	35
Ship type	Container	Container	Container	Container	Container	Container	Container

Table 4. Assigned GTT and m-EPCs.

Sub-Tasks	m-EPCs	GTT
1.1	EPC1, EPC17, EPC22, EPC23	G
1.2	EPC12, EPC15, EPC22, EPC26	G
1.3	EPC12, EPC13, EPC15, EPC22	H
1.4	EPC1, EPC9, EPC12, EPC17, EPC21, EPC22	H
1.5	EPC1, EPC2, EPC17, EPC24, EPC25, EPC26	G
2.1	EPC17, EPC22, EPC26	G
2.2	EPC11, EPC13, EPC17	H
2.3	EPC13, EPC15, EPC17	H
2.4	EPC11, EPC15, EPC24, EPC33	E
2.5	EPC11, EPC17, EPC23, EPC32	H
2.6	EPC1, EPC5, EPC17	G
2.7	EPC1, EPC9, EPC14, EPC15	E
2.8	EPC1, EPC4, EPC5, EPC9	E
2.9	EPC2, EPC9, EPC15, EPC32	E
2.10	EPC2, EPC5, EPC13, EPC20	H
2.11	EPC15, EPC17, EPC22	G
2.12	EPC5, EPC9, EPC12, EPC17, EPC24, EPC26, EPC28	H
2.13	EPC1, EPC12, EPC13, EPC20	G
2.14	EPC12, EPC21, EPC24, EPC26	G
2.15	EPC1, EPC11, EPC24, EPC26	M
2.16	EPC1, EPC13, EPC15	H
2.17	EPC2, EPC15, EPC21, EPC22, EPC29	G
2.18	EPC12, EPC13, EPC14, EPC17, EPC24	H
2.19	EPC15, EPC17, EPC21, EPC24, EPC26, EPC32	H

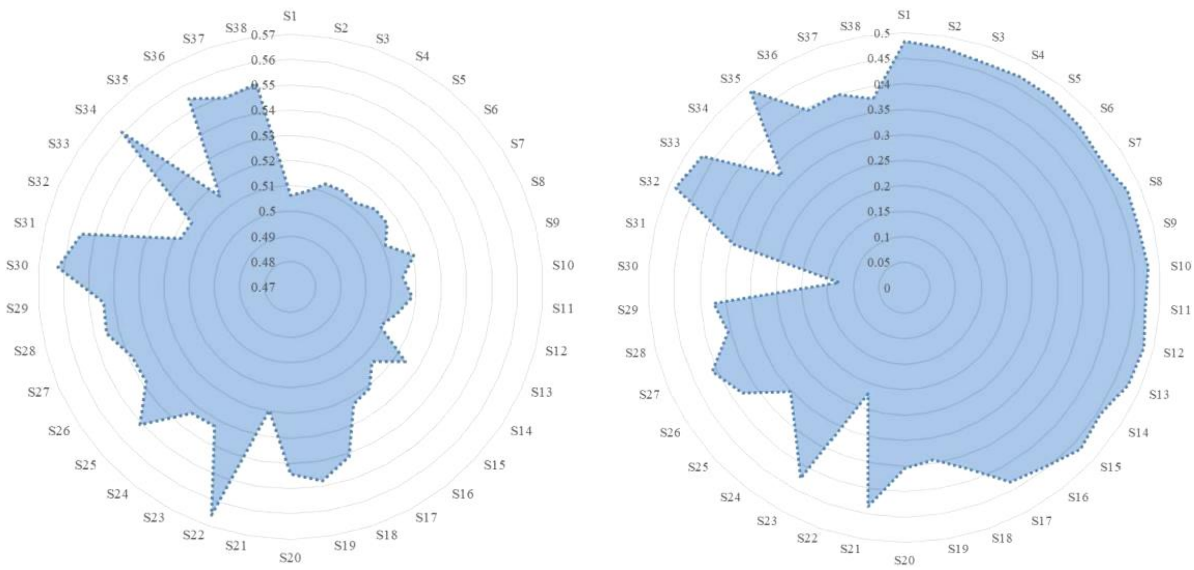

Figure 1. The weights A_{s1} (**left**) and A_{s2} (**right**).

Table 5. HEP comparisons between Scenario 1, Scenario 2, and reference data.

Sub-Task	Scenario 1	Reference Data	Scenario 2
1.1	2.59×10^{-2}	2.59×10^{-2}	2.04×10^{-2}
1.2	4.84×10^{-2}	4.85×10^{-2}	2.88×10^{-2}
1.3	7.50×10^{-3}	7.33×10^{-3}	5.00×10^{-3}
1.4	2.58×10^{-2}	2.90×10^{-2}	1.49×10^{-2}
1.5	1.48×10^{-1}	1.91×10^{-1}	9.49×10^{-2}
2.1	2.30×10^{-3}	2.46×10^{-3}	1.50×10^{-3}
2.2	1.30×10^{-3}	1.29×10^{-3}	1.10×10^{-3}
2.3	1.51×10^{-3}	1.88×10^{-3}	1.22×10^{-3}
2.4	3.41×10^{-3}	3.82×10^{-3}	2.70×10^{-3}
2.5	3.60×10^{-3}	3.58×10^{-3}	2.50×10^{-3}
2.6	2.44×10^{-2}	2.25×10^{-2}	2.03×10^{-2}
2.7	1.26×10^{-2}	1.28×10^{-2}	9.70×10^{-3}
2.8	1.01×10^{-2}	9.90×10^{-3}	8.00×10^{-3}
2.9	1.48×10^{-2}	1.47×10^{-2}	1.15×10^{-2}
2.10	7.40×10^{-3}	7.30×10^{-3}	5.10×10^{-3}
2.11	5.80×10^{-3}	5.94×10^{-3}	4.20×10^{-3}
2.12	1.39×10^{-2}	1.37×10^{-2}	7.20×10^{-3}
2.13	3.88×10^{-2}	3.95×10^{-2}	2.86×10^{-2}
2.14	1.21×10^{-1}	1.14×10^{-1}	8.36×10^{-2}
2.15	4.45×10^{-2}	4.43×10^{-2}	3.20×10^{-2}
2.16	7.30×10^{-3}	7.62×10^{-3}	5.90×10^{-3}
2.17	7.42×10^{-2}	7.45×10^{-2}	4.80×10^{-2}
2.18	8.20×10^{-3}	8.84×10^{-3}	5.80×10^{-3}
2.19	7.10×10^{-3}	7.05×10^{-3}	4.00×10^{-3}

Figure 1 demonstrates the values of A_{s1} and A_{s2}. Figure 2 shows the calculated HEP comparisons between scenario 1 (S1), scenario 2 (S2), and reference data (R), where t1.1 represents sub-task 1.1, and t1.2 means sub-task 1.2, and the remaining labels on the abscissa have a similar basis.

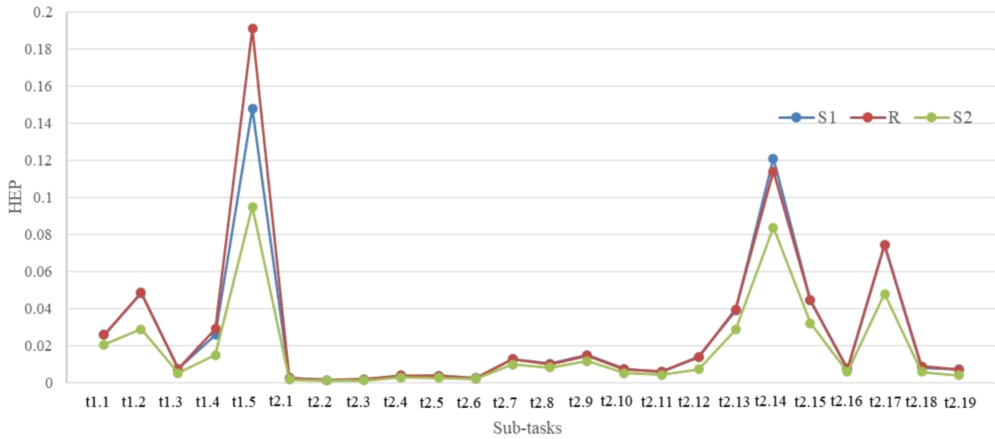

Figure 2. The HEP results of S1, S2, and reference data.

4. Findings and Discussion

The proposed approach can adequately address the operations based on the calculated results and comparison. In light of Figure 2, the results in both scenarios are in good agreement with the reference data, which implies both scenarios are reasonable attempts to calculate the HEP. However, Scenario 1 and the reference data agree better than scenario 2. This result indicates that the weights of EPCs generated by the combination of the MMOHRA model, HEART model, and SOHRA model are more reasonable than that of all six models' combinations. The probable reasons may be as follows:

(1) HEART model is the general foundation of this method; the other five approaches are modified or revised versions of the HEART model.

(2) MMOHRA model and SOHRA model were developed especially for the maritime domain, while the NARA model, CARA model, and RARA model are only for nuclear action reliability assessment, aviation action reliability assessment, and railway action reliability assessment, respectively.

The cargo loading operations of container ships are complex, as listed in Table 1. The two main parts, human safety and ship/cargo security, consist of 24 sub-tasks. Each sub-task involves more than two EPCs, as per the experts' judgments. The eight most frequently involved EPCs are EPC17, EPC15, EPC22, EPC26, EPC24, EPC12, EPC13, and EPC1, as shown in Table 6.

Table 6. The most frequently involved EPCs.

No.	EPC No.	Connotation	No.	EPC No.	Connotation
1	EPC17	Inadequate checking	5	EPC24	Absolute judgment required
2	EPC15	Operator inexperience	6	EPC12	Misperception of risk
3	EPC22	Lack of exercise	7	EPC13	Poor feedback
4	EPC26	Progress tracking lack	8	EPC1	Unfamiliarity

EPC17 (Inadequate checking) is the most frequently appearing EPC. Because the loading operation is a continuous process, all the parameters, such as draft, cargo remaining onboard, and lashing, are dynamically changing, so frequent checking is required during the operation. However, the repetition makes the crew prone to tire, and overlook easy to happen. This situation will induce accidents easily, as the safety barrier is broken at this point. EPC15 (Operator inexperience) stands in the second position, indicating the crew at the operating level does not have enough training or operation experience, as does EPC22 (lack of exercise). Enhanced training programs can remedy this gap. EPC26 (Progress tracking lack) in the loading process is a common non-conformity as per the experts' experiences. During the loading process, duty change, overlook, random errors, fatigue, etc., could suspend progress tracking. EPC24 (Absolute judgment required) is the

required content of competence. EPC12 (Misperception of risk) may occur due to mental stress, fatigue, time shortage, or inexperience. EPC13 (Poor feedback) could happen when unreliable instruments are used or misunderstanding occurs. EPC1 (Unfamiliarity) mostly appears when newly joined crew are on duty or when performing rare tasks.

According to Figure 2, the eight sub-tasks with the highest HEP are shown in Table 7. Sub-task 1.5 with the HEP value 1.48×10^{-1} is located in the first position, and sub-tasks 2.14 and 2.17 are in the second and third positions, respectively. Because they have been analyzed by Erdem et al. [1], to avoid repetition, the remaining five sub-tasks will be discussed in detail.

Table 7. Sub-tasks with the highest HEP.

No.	Sub-Tasks
1	1.5 Be aware of the risks of lashing operations on bays at which cargo operations are occurring
2	2.14 Check if the leakage containers onboard
3	2.17 Inform the charterer and management office if the container is heavily damaged
4	1.2 Use safety belt when working/climbing on containers
5	2.15 Inform C/O in case damaged container is observed
6	2.13 Inform C/O if hook spreaders are used for cargo operations
7	1.1 Make sure that all crew on deck use PPE
8	1.4 Be aware of the risks of mislaid equipment on operated container

Sub-task 1.2 (4.84×10^{-2}) refers to the safety belt while working or climbing on containers. The safety belt is used to protect crew safety. However, modern loading operations emphasize efficiency heavily. The continuous loading process requires endless checking and lashing work but limited time to finish the job. These factors probably increase the mental stress of the duty crew and thus increase the HEP when performing the task. Sub-tasks 2.15 (4.45×10^{-2}) and 2.13 (3.88×10^{-2}) are similar work involving inspection and reporting. Such work may go unnoticed for insufficient inspection rather than for reporting reasons. Table 6 provides the evidence that shows that EPC1 is assigned in both cases. Sub-task 1.1 (2.59×10^{-2}) refers to the proper usage of PPE while working on deck. This task involves safety regulation and safety awareness. It should be common sense that proper PPE should be worn whenever working on deck. Sub-task 1.4 (2.58×10^{-2}) also has a higher HEP value than the remaining sub-tasks, because this kind of risk is not obvious. It takes more time to find the mislaid equipment in an operated container. In contrast, limited time makes it easy to increase the probability of human errors.

The sub-tasks with higher HEP do not indicate that human errors will happen certainly but imply decreased reliability. Meanwhile, the potential risks are increasing. Therefore, a series of error reduction measures are recommended to reduce the chances of the error happening to manage the crew's reliability and strengthen the safety level for this loading operation (Table 8).

Table 8. Recommendations for HEP mitigation.

Sub-Task	EPC	Mitigate Measures
1.5	EPC1	1. Nominate an experienced crew to supervise the lashing operation nearby. 2. Potential dangers should be reminded to the operators
	EPC2	1. Safety meeting to be held before the operation 2. Teamwork is required during performing the task
	EPC17	1. Adequate communication should be maintained 2. Proper instructions should be illustrated before the task
	EPC24	1. Reminders should be made in time in case the situation changes 2. Nominate an experienced crew to help and supervise
	EPC25	1. Proper PPE should be worn before the task 2. The task should be performed according to Chief Mate's instruction
	EPC26	1. Enhance crew situation awareness through adequate training

Table 8. *Cont.*

Sub-Task	EPC	Mitigate Measures
2.14	EPC12	1. Periodical exercises concerning checking the container leakage should be held 2. Any doubt about the container leakage should be reported to Chief Mate
	EPC21	1. Arrange experienced crew while checking to increase the reliability 2. Effective communication should be maintained
	EPC24	1. Necessary training should be performed 2. Checking should be carried out as per instruction
	EPC26	1. Proper records should be kept 2. Procedures should be followed and supervised
2.17	EPC2	1. Prepare reporting templates in case of emergency use 2. Inform the Master earlier in case of emergency
	EPC15	1. Adequate cooperation is required 2. Experienced Master is preferred
	EPC21	1. Incentives should comply with the regulations
	EPC22	1. Frequent training concerning emergency handling should be performed 2. The emergency checklist should be filled up in case any critical steps missing
	EPC29	1. Avoid shouting while communicating 2. More encouragement is suggested during working
1.2	EPC12	1. Arrange a supervisor for this kind of work 2. Adequate reminders should be maintained
	EPC15	1. Safety meeting should be held before commencing work 2. An experienced crew is required to give help and advice
	EPC22	1. Safety checklist should be finished by themselves before working 2. Periodical exercises should be carried out
	EPC26	1. Update the progress in time as per instruction 2. Periodical supervise should be maintained
2.15	EPC1	1. Regular exercises should be held to identify various damaged containers 2. Teamwork is required during performing the task
	EPC11	1. Adequate reminders should be maintained 2. An experienced crew is required to give help and advice
	EPC24	1. Adequate cooperation is required 2. Experienced crew should be assigned to the critical task
	EPC26	1. Update the progress in time as per instruction
2.13	EPC1	1. Periodical checking should be carried out 2. Safety meetings should be held before working
	EPC12	1. Arrange a supervisor for this kind of work 2. Ask for help when the vague danger exists
	EPC13	1. Adequate communication should be kept 2. Reports accordingly as per instruction
	EPC20	1. Demonstration of the task should be exercised 2. Proper training should be held as per the regulation
1.1	EPC1	1. Post the safety instructions in the crew changing room 2. Safety meetings should be held before working
	EPC17	1. The checklist should be filled up before leaving the changing room 2. Periodical supervision should be maintained
	EPC22	1. Periodical exercises should be carried out 2. Demonstration of the task should be exercised
	EPC23	1. Check the equipment before working 2. Proper instruments should be assigned

Table 8. *Cont.*

Sub-Task	EPC	Mitigate Measures
1.4	EPC1	1. Training and exercise should be held to become familiar with the task 2. Teamwork is preferred to reduce one-man error
	EPC9	1. Demonstration of the task should be exercised 2. Experienced crew should be assigned to the critical task
	EPC12	1. Adequate supervision should be kept 2. Strengthen risk awareness through regular safety meetings
	EPC17	1. Adequate communication should be maintained 2. Regular checking should be kept
	EPC21	1. Proper incentives to encourage crew motivation 2. Adequate communication should be kept
	EPC22	1. Periodical exercises should be carried out 2. Safety awareness should be strengthened through demonstration

5. Conclusions

It is impossible to prevent all human errors, but it is possible to minimize their rate of occurrence. Presently, safe and reliable operations onboard ships depend on human reliability. Human error is a dominant factor that can influence human reliability. Therefore, studying human error is significant for controlling human reliability. This article proposes a novel hybrid approach by incorporating the SOHRA model, entropy weight method, and TOPSIS model to calculate human error probability. The entropy weighted TOPSIS approach could effectively reduce subjectivity by replacing the experts' weighting. The weights determined by this method can be modified as well. After comparing with the reference data, it can be concluded that this method is effective. Further, Scenario 1 is better than the other scenario when analyzing their calculated results, which implies the combination of MMOHRA, SOHRA, and HEART models could provide better results concerning the proportions of EPCs. Through this research, an alternative way to obtain the proportions of EPCs is utilized and proved effective.

According to its background, this method could be utilized in various crew operations onboard ships, including deck and engine crew operations. Since differences exist between the deck and engine departments, more specific models could be developed to obtain more accurate HEP values. However, experts' judgments significantly influence this research process. The main reason is that scant human error information could be obtained for the research. At least two methods can be implemented to minimize the subjectivity of experts' decisions. One is the utilization of the Delphi method [46]. The other is to collect enough human error information. Modern technology such as monitoring and recording systems could record human error scenarios, and then, based on the recorded scenarios, the investigation reports of human errors can be obtained, similar to the reports of the Marine Accident Investigation Branch (MAIB, UK) or Australia Transport Safety Bureau (ATSB, Australia). This process could be conducted by companies or government organizations. After adequate human error information is collected, the experts' judgments can be replaced.

Author Contributions: Conceptualization, methodology, software, validation, formal analysis, writing—original draft preparation, writing—review and editing, X.M.; supervision, validation, formal analysis, G.S. and W.L.; formal analysis, writing—review and editing, J.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number 51579025.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Erdem, P.; Akyuz, E. An interval type-2 fuzzy SLIM approach to predict human error in maritime transportation. *Ocean Eng.* **2021**, *232*, 109161. [CrossRef]
2. Akyuz, E. Quantitative human error assessment during abandon ship procedures in maritime transportation. *Ocean Eng.* **2016**, *120*, 21–29. [CrossRef]
3. Xi, Y.T.; Yang, Z.L.; Fang, Q.G.; Chen, W.J.; Wang, J. A new hybrid approach to human error probability quantification- applications in maritime operations. *Ocean Eng.* **2017**, *138*, 45–54. [CrossRef]
4. Kandemir, C.; Celik, M. Determining the error producing conditions in marine engineering maintenance and operations through HFACS-MMO. *Reliab. Eng. Syst. Saf.* **2021**, *206*, 107308. [CrossRef]
5. Zhou, Q.J.; Wong, Y.D.; Xu, H.; Thai, V.V.; Loh, H.S.; Yuen, K.F. An enhanced CREAM with stakeholder-graded protocols for tanker shipping safety Ap-plication. *Saf. Sci.* **2017**, *95*, 140–147. [CrossRef]
6. Akyuz, E.; Celik, M.; Cebi, S. A Phase of Comprehensive research to determine marine-specific EPC values in human error assessment and reduction technique. *Saf. Sci.* **2016**, *87*, 63–75. [CrossRef]
7. Read, G.J.M.; Shorrock, S.; Walker, G.H.; Salmon, P.M. Ience: Evolving perspectives on 'Human Error'. *Ergonomics* **2021**, *64*, 1091–1114. [CrossRef]
8. Heinrich, H.W. *Industrial Accident Prevention: A Scientific Approach*; McGraw-Hill: New York, NY, USA, 1931.
9. Kirwan, B.; Gibson, H. CARA: A Human reliability assessment tool for air traffic safety management technical basis and preliminary architecture. In *The Safety of Systems*; Springer: Berlin, Germany, 2007; pp. 197–214.
10. Kirwan, B.; Gibson, H.; Kennedy, R.; Edmunds, J.; Cooksley, G.; Umbers, I. Nuclear Action Reliability Assessment (NARA): A Data-Based HRA Tool. In *Probabilistic Safety Assessment and Management*; Springer: Berlin, Germany, 2004; pp. 1206–1211.
11. Gibson, W.; Mills, A.M.; Smith, S.; Kirwan, B.K. Railway action reliability assessment a railway specific approach to human error quantification. In Proceedings of the Australian System Safety Conference, Adelaide, Australia, 22–24 May 2013; Volume 145, pp. 3–8.
12. Wang, W.; Liu, X.; Qin, Y. A Modified HEART method with FANP for human error assessment in high speed railway dispatching tasks. *Int. J. Ind. Ergon.* **2018**, *67*, 242–258. [CrossRef]
13. Torres, Y.; Nadeau, S.; Landau, K. Classification and quantification of human error in manufacturing. A case study in complex manual assembly. *Appl. Sci.* **2021**, *11*, 749. [CrossRef]
14. Kumar, P.; Gupta, S.; Gunda, Y.R. Estimation of human error rate in underground coal mines through retrospective analysis of mining accident reports and some error reduction strategies. *Saf. Sci.* **2020**, *123*, 104555. [CrossRef]
15. Hsieh, M.; Wang, E.M.; Lee, W.; Li, L.; Hsieh, C.; Tsai, W.; Wang, C.; Huang, J.; Liu, T. Application of HFACS, Fuzzy TOPSIS, and AHP for Identifying Important Hu-Man Error Factors in Emergency Departments in Taiwan. *Int. J. Ind. Ergon.* **2018**, *67*, 171–179. [CrossRef]
16. Sameera, V.; Bindra, A.; Rath, G.P. Human errors and their prevention in healthcare. *J. Anaesthesiol. Clin. Pharmacol.* **2021**, *37*, 328–335. [CrossRef]
17. Hu, W.; Carver, J.C.; Anu, V.; Walia, G.S.; Bradshaw, G.L. Using human error information for error prevention. *Empir. Softw. Eng.* **2018**, *23*, 3768–3800. [CrossRef]
18. Ung, S.-T. Evaluation of human error contribution to oil tanker collision using fault tree analysis and modified fuzzy bayesian network based CREAM. *Ocean Eng.* **2019**, *179*, 159–172. [CrossRef]
19. Zhou, J.L.; Yi, L. A slim integrated with empirical study and network analysis for human error assessment in the railway driving process. *Reliab. Eng. Syst. Saf.* **2020**, *204*, 107148. [CrossRef]
20. Ahn, S.I.; Kurt, R.E. Application of a CREAM based framework to assess human reliability in emergency re-sponse to engine room fires on ships. *Ocean Eng.* **2020**, *216*, 108078. [CrossRef]
21. Zhang, R.; Tan, H.; Afzal, W. A Modified Human Reliability Analysis Method for the Estimation of Human Error Probability in the Offloading Operations at Oil Terminals. *Process Saf. Prog.* **2020**, *40*, 84–92. [CrossRef]
22. Kandemir, C.; Celik, M. A human reliability assessment of marine auxiliary machinery maintenance operations under ship PMS and maintenance 4.0 concepts. *Cogn. Tech. Work* **2020**, *22*, 473–487. [CrossRef]
23. Islam, R.; Yu, H.; Abbassi, R.; Garaniya, V.; Khan, F. Development of a monograph for human error likelihood assessment in marine operations. *Saf. Sci.* **2017**, *91*, 33–39. [CrossRef]
24. Williams, J.C. A data-based method for assessing and reducing human error to improve operational performance. In Proceedings of the IEEE 4th Conference on Human Factor and Power Plants, Monterey, CA, USA, 5–9 June 1988; pp. 436–450. [CrossRef]
25. Akyuz, E.; Celik, M. A methodological extension to human reliability analysis for cargo tank cleaning operation on board chemical tanker ships. *Saf. Sci.* **2015**, *75*, 146–155. [CrossRef]
26. Akyuz, E.; Celik, E. A Modified human reliability analysis for cargo operation in single point mooring (SPM) off-shore units. *Appl. Ocean Res.* **2016**, *58*, 11–20. [CrossRef]
27. Wang, W.; Liu, X.; Liu, S. A hybrid evaluation method for human error probability by using extended DEMATEL with Z-numbers: A case of cargo loading operation. *Int. J. Ind. Ergon.* **2021**, *84*, 103158. [CrossRef]

28. Embrey, D.E.; Humphreys, P.C.; Rosa, E.A.; Kirwan, B.; Rea, K. *SLIM-MAUD: An Approach to Assessing Human Error Probabilities Using Structured Expert Judgement*; United States Nuclear Regulatory Commission: North Bethesda, MD, USA, 1984.
29. Islam, R.A.; Abbassi, R.; Garaniya, V.; Khan, F.I. Determination of human error probabilities for the maintenance operations of marine engines. *J. Ship Prod. Des.* **2016**, *32*, 226–234. [CrossRef]
30. Hollnagel, E. *Cognitive Reliability and Error Analysis Method*; Elsevier: Amsterdam, The Netherlands, 1998. [CrossRef]
31. Akyuz, E. Quantification of human error probability towards the gas inerting process on-board crude oil tankers. *Saf. Sci.* **2015**, *80*, 77–86. [CrossRef]
32. Yang, Z.L.; Abujaafar, K.M.; Qu, Z.; Wang, J.; Nazir, S.; Wan, C. Use of evidential reasoning for eliciting bayesian subjective probabilities in human reliability analysis: A maritime case. *Ocean Eng.* **2019**, *186*, 106095. [CrossRef]
33. Zhou, Q.J.; Wong, Y.D.; Loh, H.S.; Yuen, K.F. A fuzzy and bayesian network CREAM model for human reliability analysis—The case of tanker shipping. *Saf. Sci.* **2018**, *105*, 149–157. [CrossRef]
34. Shirali, G.A.; Hosseinzadeh, T.; Ahamadi Angali, K.; Rostam Niakan Kalhori, S. Modifying a method for human reliability assessment based on cream-Bn: A case study in control room of a petrochemical plant. *MethodsX* **2019**, *6*, 300–315. [CrossRef]
35. Wu, B.; Yan, X.; Wang, Y.; Soares, C.G. An Evidential Reasoning-Based Cream to Human Reliability Analysis in Maritime Accident Process. *Risk Anal.* **2017**, *37*, 1936–1957. [CrossRef]
36. Li, G.; Weng, J.; Hou, Z. Impact analysis of external factors on human errors using the ARBN method based on small-sample ship collision records. *Ocean Eng.* **2021**, *236*, 109533. [CrossRef]
37. Swain, A.D.; Guttmann, H.E. *Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications*; Report No. NUREG/CR-1278; United States Nuclear Regulatory Commission: North Bethesda, MD, USA, 1983.
38. Zhang, M.; Zhang, D.; Yao, H.; Zhang, K. A probabilistic model of human error assessment for autonomous cargo ships focusing on human—Autonomy collaboration. *Saf. Sci.* **2020**, *130*, 104838. [CrossRef]
39. El-Ladan, S.B.; Turan, O. Human reliability analysis—Taxonomy and praxes of human entropy boundary conditions for marine and offshore applications. *Reliab. Eng. Syst. Saf.* **2012**, *98*, 43–54. [CrossRef]
40. Abrishami, S.; Khakzad, N.; Hosseini, S.M. A data-based comparison of BN-HRA models in assessing human error proba-bility: An offshore evacuation case study. *Reliab. Eng. Syst. Saf.* **2020**, *202*, 107043. [CrossRef]
41. Cooper, S.E.; Ramey-Smith, A.M.; Wreathall, J.; Parry, G.W. *A Technique for Human Error Analysis (ATHEANA): Technical Basis and Methodology Description*; Nureg/CR-6350; USNRC: North Bethesda, MD, USA, 1996; p. 996.
42. Akyuz, E.; Celik, M.; Akgun, I.; Cicek, K. Prediction of human error probabilities in a critical marine engineering operation on-board chemical tanker ship: The case of ship bunkering. *Saf. Sci.* **2018**, *110*, 102–109. [CrossRef]
43. Shannon, C.E. A mathematical theory of communication. *SIGMOBILE Mob. Comput. Commun. Rev.* **2001**, *5*, 3–55. [CrossRef]
44. Hwang, C.L.; Yoon, K. *Multiple Attribute Decision-Making Methods and Application*; Springer: Berlin, Germany, 1981.
45. Chen, J.; Bian, W.; Wan, Z.; Yang, Z.; Zheng, H.; Wang, P. Identifying factors influencing total-loss marine accidents in the world: Analysis and eva lu-ation based on ship types and sea regions. *Ocean Eng.* **2019**, *191*, 106495. [CrossRef]
46. Duru, O.; Bulut, E.; Yoshida, S. A fuzzy extended DELPHI method for adjustment of statistical time series prediction: An empirical study on dry bulk freight market case. *Expert Syst. Appl.* **2012**, *39*, 840–848. [CrossRef]