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Comprehensive Analysis of Navigational Accidents Using the MAART Method: A Novel Examination of Human Error Probability in Maritime Collisions and Groundings

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ABSTRACT: Navigational accidents are one of the most common types of maritime accidents, and they can result from various factors, including human error, adverse weather conditions, technical issues with the ship, or a combination of these factors. In this study, navigational accidents, including collision and grounding, that occurred in Germany were analysed using the MAART method. The novelty of this research lies in its detailed examination of the Human Error Probability (HEP) result, which has yet to be explored in previous studies. There are 47 collision cases and 15 grounding cases in the 13-year occurrence period. In total, 290 causal factors were found in the analysis. Furthermore, it is found that management, media, and machines are the main causal factors in navigational accidents in Germany. In collision accidents, management factors had the highest number of contributing factors, followed by media and machine factors. Contrary to grounding accidents, based on the results of the EPC, the machine factor had the highest number of contributing factors to accidents, followed by media and management. Finally, the human error probability values for collision accidents range from 0.06 to 1, averaging 0.54. In contrast, the HEP values for grounding accidents range from 0.0048 to 1, averaging 0.26.

1 INTRODUCTION

Maritime accidents are a frequent occurrence that can cause significant losses. This is due to the increasing complexity and dynamism of the ship environment, resulting from the rising number and size of vessels [1], [2], [3], [4], [5], [6]. Navigational accidents are one of the most common types of maritime accidents, and they can result from various factors, including human error, adverse weather conditions, technical issues with the ship, or a combination of these factors [7].

The effects of navigational accidents can be severe and destructive, mainly if the collision involves ships carrying hazardous materials or a high volume of ship traffic. This study has two types of navigational accidents: collision and grounding. Navigational accidents can cause physical damage to the ships, including their hulls and engines. They can risk environmental damage, such as oil spills or other hazardous substances released into the sea. Different types of navigational accidents, such as collisions with other ships, bridges, or docks, can result in significant casualties, as the impact force can cause severe damage and potentially lead to sinking. Crew members, passengers, and those in the surrounding area can also be endangered [8] [9].

In many cases, the costs of ship accidents outweigh the costs of preventing them. For example, in cases of ship sinking, the loss is not only calculated from the loss of the ship but also from the value of the lost cargo [10]. According to Lloyd's Register Intelligence Casualty statistics, 3,976 maritime accidents have occurred where a ship lost more than 100 gross tonnes, resulting in 15,738 deaths [11].

Navigational accident risk assessment has become a crucial aspect of maritime safety and traffic management in reducing the number of ship collisions. Research has indicated that navigational conflicts are the leading cause of ship collisions [12]. To prevent maritime accidents globally, the International Convention on Standards for Training, Certification, and Supervision, ISM, and the International Regulations for Preventing Collisions at Sea have been put in place. A better understanding of the human element and strategies to mitigate human errors can help prevent accidents [13]. Human reliability analysis (HRA) is a technique that predicts the safety of particular activities involving people. HRA considers various factors that may lead to human errors and the potential outcomes of such errors. HRA has been widely employed in assessing risk and estimating the likelihood of human error in specific activities [14] [15] [16] [17].

There are several methods for estimating the probability of human error (HEP) in different systems, including THERP (Technique for Human Error Rate Prediction), ATHEANA (Analytical Technique for Human Error Analysis), and SHERPA (Systematic Human Error Reduction and Prediction Approach) models [18]. CREAM is a method for measuring data reliability that considers how often people answer questions correctly, even when faced with time constraints. SPAR-H is similar but focuses on how frequently people make mistakes, while HCR assesses how likely people are to respond correctly regardless of time constraints. The HEART technique is used to minimise the chances of people making mistakes. Until recently, HRA has been used to evaluate risks for complex systems. However, the cognitive-based THERP (CB-THERP) method, which integrates DSA, THERP, and HCR, has been developed to quantify human exposure in nuclear power plants after an accident [19].

HEART is a flexible and easy-to-use method for analysing accidents in various industries, such as aviation, rail, offshore drilling, and maritime operations [20], [21], [22], dan [23], [24]. HRA is used to assist with risk assessment for complex systems. Islam et al. modified the HEART method to evaluate and measure human error in maritime, environmental, and operational conditions to enhance the safety and reliability of maintenance and repair practices [25]. Akyuz et al. employed the HEART and type-2 fuzzy interval sets to assess human reliability in cargo operations [26].

According to de Maya's research, the combination of Hierarchical Task Analysis (HTA) and the Human Error Assessment and Reduction Technique (HEART) can be used to predict potential errors that may occur when handling fires on passenger ships [27]. Another study by W. Wang et al. demonstrated that by modifying the HEART method with the Railway Action Reliability Assessment (RARA) technique and the fuzzy analytic network process (FANP), it is possible to evaluate the likelihood of human error in high-speed rail [28]. Bowo's study proposes a hybrid methodology for assessing human errors by integrating the HEART-4M method with a new approach called Maritime Accident Analysis and Reduction Techniques (MAART) [29]. Bowo [30] has recently conducted an MAART study for collision accidents. Studies with different accident cases, such as sinking and collisions, should be performed to enhance and delve more into MAART's capability to analyse the probability of human error. The new phenomena could be explored within MAART by adding different accident types, cases, and data.

This study aims to investigate the influence of human error on collision and grounding accidents by using the MAART method. This work is a development of earlier MAART studies that incorporate the grounding accident. The disparity and correlation between the two accidents will be defined and assessed. The novelty of this research is the emphasis on examining HEP results, which needs to receive more attention in previous studies.

2 DATA AND METHODOLOGY

This study's maritime navigational accident data consists of Germany's collision and grounding accidents from 2008 to 2020. The data will be analysed qualitatively and quantitatively by using MAART.

2.1 *Data*

The official accident report is considered reliable secondary data because it has been created by accident investigators by interviewing and analysing the primary data source [31,32]. The maritime navigational accident data reports are retrieved from the Federal Bureau of Maritime Casualty Investigation (BSU) website in Germany. The analysed accident reports occurred from 2008 to 2020, as shown in Table 1 below. During this period, 30 collisions were reported, with the highest number occurring in 2008 and the most recent in 2017. Groundings were more common than collisions, with a total of 47 incidents reported. The highest number of groundings occurred in 2013, while 2016 and 2017 saw the fewest incidents. The accident reports that were collected are limited to English-written reports. Therefore, it has been several years with no data reports. In collision cases, if there is information about two or more ships involved, those ships will be analysed separately. From 31 data reports of collision, 48 ships were analysed. Therefore, in total, there are 48 data reports and 62 ships analysed.

Microsoft Excel software is utilised to record the data and tabulate it. The data that is extracted from the data reports include accident time, type of ships, accident locations, weather conditions, and causal factors of the accidents. To prevent subjectivity of the data extraction, the authors only stated the causal factors written in the data reports; no self-opinion is included in the analysis. The calculation of the Human Error Probability (HEP) also uses Microsoft Excel.

Table 1. Maritime Navigational Accidents Data Reports

Year	Collision Data	Collision Ships	Grounding
2008	8	12	2
2009	1	2	-
2010	1	2	-
2011	2	3	2
2012	-	-	2
2013	5	9	1
2014	7	12	1
2015	4	4	1
2016	1	1	2
2017	1	2	1
2018	-	-	1
2019	-	-	1
2020	-	-	1
Total	30	47	15

2.2 *Methodology*

The maritime navigational data in this study is analysed using the Maritime Accident Analysis And Reduction Technique (MAART). MAART is a method to find out how likely something will happen in the maritime industry by combining the HEART – 4M method approach and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to evaluate Human Error Probability (HEP) [33]. This method divided the analysis into two stages: the qualitative stage and the quantitative stage. Figure 1 below shows the framework of the MAART method stages.

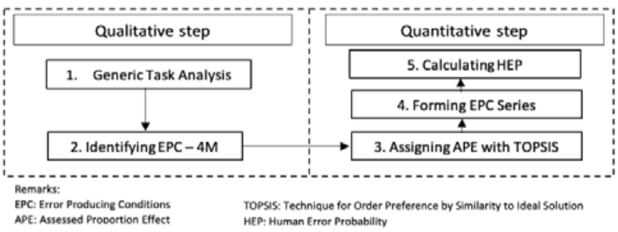

Figure 1. MAART method stages [33]

2.2.1 *Qualitative stage*

In the qualitative stage, the working conditions and causal factors of the accidents are analysed. Firstly, the working conditions when the accidents occurred are determined. In this step, the working condition will be matched with nine Generic Tasks (GT) in the MAART method. These GTs are categorised into two categories: challenging tasks and convenient tasks. The challenging task category consists of three working conditions, with the highest nominal human unreliability (NHU) associated with unfamiliarity with the working conditions.

On the other hand, the convenient task category includes six working conditions, with the lowest NHU associated with a highly familiar, highly practised, routine task occurring several times per hour, performed to the highest possible standards by a highly motivated, highly trained, and experienced person. The NHU values are an indication of the likelihood of errors occurring during the task performance. This information can be used to identify areas where human error is likely to occur and to develop appropriate measures to prevent accidents in the maritime industry. Table 2 below shows the GTs used in this study.

Table 2. Generic Tasks

Code	Working condition	NHU
Challenging Task		
A	Unfamiliar with the condition	0.55000
B	Reinstate the system to its original state on a single attempt	0.26000
C	Complex task	0.16000
Convenient Task		
D	An adequately simple task	0.09000
E	The routine, highly practiced, rapid task	0.02000
F	Reinstate the system to its original state	0.00300
G	Entirely familiar, highly practiced, routine task occurring several times per hour, performed to the highest possible standards by a highly motivated, highly trained, and experienced person	0.00040
H	Respond correctly to the system instruction	0.00002
M	The miscellaneous task for which no description can be found.	0.03000

Table 3. Error Producing Conditions [34]

Man Factor		
1. Experience		
EPC 1	Unfamiliarity	(x 17)
EPC 12	Misperception of risk	(x 4)
EPC 22	Lack of experience	(x 1.8)
2. Skill and Knowledge		
EPC 7	Irreversibility	(x 8)
EPC 9	Technique unlearning	(x 6)
EPC 11	Performance ambiguity	(x 5)
EPC 15	Operator inexperience	(x 3)
EPC 20	Educational mismatch	(x 2)
3. Psychological		
EPC 21	Dangerous incentives	(x 2)
EPC 28	Low meaning	(x 1.4)
EPC 29	Emotional stress	(x 1.3)
EPC 31	Low morale	(x 1.2)
EPC 34	Low mental workload	(x 1.1)
4. Physical		
EPC 27	Physical capabilities	(x 1.4)
EPC 36	Task pacing	(x 1.06)
EPC 38	Age	(x 1.02)
5. Health		
EPC 30	Ill-health	(x 1.2)
EPC 35	Sleep cycle disruption	(x 1.1)
Media Factor		
EPC 33	Poor environment	(x 1.15)
Machine Factor		
EPC 3	Low signal-noise ratio	(x 10)
EPC 8	Channel overload	(x 6)
EPC 23	Unreliable instruments	(x 1.6)
Management Factor		
1. Coordination		
EPC 2	Time shortage	(x 11)
EPC 6	Model mismatch	(x 8)
EPC 24	Absolute judgments required	(x 1.6)
EPC 25	Unclear allocation of function	(x 1.6)
EPC 37	Supernumeraries/ lack of human resources	(x 1.03)
2. Rules and procedures		
EPC 4	Features over-ride allowed	(x 9)
EPC 5	Spatial and functional incompatibility	(x 8)
EPC 32	Inconsistency of displays	(x 1.2)
3. Communication		
EPC 10	Knowledge transfer	(x 5.5)
EPC 13	Poor feedback	(x 4)
EPC 14	Delayed/incomplete feedback	(x 3)
EPC 16	Impoverished information	(x 3)
EPC 18	Objectives conflict	(x 2.5)
EPC 19	No diversity of information	(x 2.5)
4. Monitoring		
EPC 17	Inadequate checking	(x 3)
EPC 26	Progress tracking lack	(x 1.4)

Following the identification of working conditions, the causal factors of the accidents are analysed in the qualitative stage. To determine the causal factors, the analysis and conclusions sections of the data reports are scrutinised, and every causal factor that is found in the MAART method is recorded. The MAART method categorises causal factors as Error Producing Conditions (EPC), of which there are 38. These factors are classified into four categories, namely, man, machine, media, and management factors. This categorisation helps prioritise the mitigation and resolution of incidents from a specific standpoint. Additionally, every EPC has a multiplier assigned to it to determine its weight in the quantitative stage. The multiplier values vary for each EPC and are indicative of the rarity of their occurrence in the cases.

Table 3 provides a comprehensive categorisation of each EPC into the four categories mentioned above and its multiplier. While the factors of media and machine do not have sub-factors, the man factors have more factors categorised and further sub-factors.

2.2.2 *Quantitative stage*

In the quantitative stage, all the qualitative data that obtained in the qualitative stage will be quantified to calculate the value of Human Error Probability (HEP). First, the weight for every obtained EPC, namely the Assessed Proportion Effect (APE), is assigned by using TOPSIS calculation to calculate the Assessed Effect (AIV) as stated in Equation 1. After calculating the weight for every EPC, then forming the EPC series by arranging the weightiest APE to the less APE. By this information, the researchers may know which factor is the main causal factor of the accidents and what kind of series of actions that might influence the condition to the occurrences. The TOPSIS calculation was conducted as has been performed by Bowo et al. [30].

$$AIV = \left\{ \prod_i (EPC_i - 1) APE_i + 1 \right\} \tag{1}$$

After determining the AIV value for each EPC, the last step is to calculate the HEP value using Equation 2.

$$HEP_{value} = NHU \cdot \left\{ \prod_i AIV_i \right\} \tag{2}$$

3 RESULTS

The results of maritime navigational accidents analysis are separated into three parts of explanation as below:

3.1 *Type of works*

Analysing the type of work when maritime navigational accidents occur can describe the situation right before the accidents occur. Maritime navigational accidents differ in two types: collision and grounding. The results for collision and grounding accidents are different. Whereas in the collision accidents, more accidents occurred during challenging tasks rather than the convenient task, and vice versa for the grounding accident.s Furthermore, not all types of work are applied in navigational accidents. Table 4 shows the results of the generic task found in the analysis.

Table 4 presents a breakdown of the type of work being performed during maritime navigational accidents, categorised by the severity of the task. The table includes two categories of tasks: challenging tasks and convenient tasks. Challenging tasks are further classified into two subcategories: type B tasks, which involve reinstating the system to its original state on a single attempt, and type C tasks, which are complex tasks. On the other hand, convenient tasks are also classified into two subcategories: type D tasks, which involve adequately simple tasks, and type E tasks, which are routine, highly practised, and rapid tasks. Additionally, there is a category called type F tasks, which involve reinstating the system to its original state, and there were no reported occurrences of this type of task during collisions. The table shows that type C tasks were the most common tasks being performed during both collision and grounding accidents, accounting for 25 and 5 occurrences, respectively. Type D tasks were the next most common type of task, with 18 occurrences during collisions and four during groundings. Type E tasks occurred three times during collisions and five times during groundings. Finally, there was only one reported incident of type B tasks during collisions and no reported incidents during groundings, and one reported incident of type F tasks during groundings and none during collisions.

Table 4. Generic Tasks analysis result

Generic Tasks	Collision	Grounding	Total
Challenging Tasks			
B	1	-	1
C	25	5	30
Convenient Tasks			
D	18	4	22
E	3	5	8
F	-	1	1

3.2 *Causal factors*

There are 290 causal factors from 62 involved ships found in the analysis of maritime navigational accidents. All 4M factors are causal factors involved in the accidents.

3.2.1 *Man factors*

Figure 3 presents the analysis of the causal factors in collision and grounding accidents with respect to the man factor. The analysis shows that experience, skill, and knowledge are significant factors in both types of accidents. However, there are some notable differences in the contributing EPCs for each type of accident.

For experience, EPC 1 has a higher value in collision accidents with a score of 5, compared to only 1 in grounding accidents. On the other hand, EPC 12 has a much higher value in collision accidents, with a score of 16, compared to 7 in grounding accidents. This indicates that the importance of experience is more significant in collision accidents, where complex and challenging situations require high levels of experience.

For skill and knowledge, EPC 7, which refers to irreversibility, has a higher value in collision accidents with a score of 8, compared to a score of 0 in grounding accidents. This suggests that the ability to reverse actions and decisions is more critical in collision accidents. EPC 11, which refers to performance ambiguity, has a higher value in collision accidents with a score of 6, while it does not have any score in grounding accidents. This indicates that clarity and precision in decision-making are more critical in collision accidents.

In terms of psychological factors, dangerous incentives (EPC 21) have a higher value in collision accidents, with a score of 8, compared to 0 in grounding accidents. This suggests that external pressures or motivations may contribute to decision-making in collision accidents. Emotional stress (EPC 29) and low mental workload (EPC 34) also have higher values in collision accidents with scores of 2 and 4, respectively, compared to only 1 and 0 in grounding accidents.

Regarding physical factors, task pacing (EPC 36) has a higher value in collision accidents with a score of 10, compared to only 0 in grounding accidents. This indicates that the pace of task execution is a more significant contributing factor in collision accidents.

Finally, sleep cycle disruption (EPC 35) has the same value for both types of accidents, with a score of 1. This suggests that sleep cycle disruption is an important physical factor contributing to collision and grounding accidents.

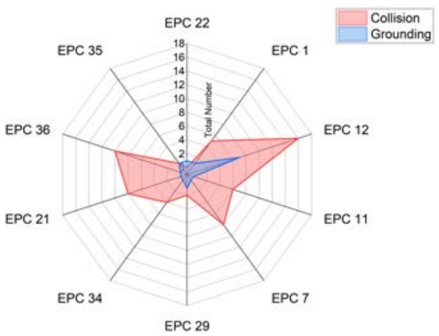

Figure 3. “Man” causal factors

3.2.2 *Media and Machine Factors*

Figure 4 shows the number of media and machine factors occurrences in collision and grounding maritime accidents. Media and machine factors were also found to influence maritime navigational accidents. The total number of media factors is 28 EPCs from 62 ships analysed. Collision and grounding accidents account for about 50% of the collected data, which shows that the media influences accidents. The media factor covers the environmental situation, which may influence the condition of the seafarers in performing the task. The media factor represented by EPC 33 shows a higher occurrence in collision accidents, with 21 instances recorded compared to 7 in grounding accidents.

On the other hand, the machine factor, represented by EPC 3 and EPC 23, shows a higher occurrence of grounding accidents relative to the machine factor in the same category. This suggests that media factors are more likely to contribute to collision accidents, while machine factors are more likely to contribute to grounding accidents.

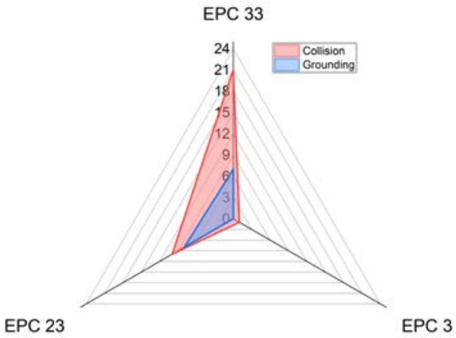

Figure 4. Media and machine causal factors

3.2.3 *Management factors*

Management factors significantly influence maritime navigational accidents, serving as both main causal and contributing factors. Of the 172 EPCs associated with management factors, only EPC 4 does not contribute to these accidents. Figure 5 illustrates the distribution of each selected EPC in collision and grounding accidents. Communication emerges as the most common problem faced by seafarers on the bridge during navigational accidents. Poor feedback, information, knowledge transfer, and diversity of information can lead to situations where seafarers on the bridge make the wrong decisions. As seen in these cases, lack of monitoring is the second most common causal factor, making accidents hard to prevent. Communication and monitoring issues in maritime navigational accidents, such as collisions and groundings, are often linked to a breakdown in the exchange of information between seafarers responsible for navigation and communication. Poor communication also affects coordination among seafarers on the bridge. Coordination sub-factors also include 29 EPCs. Additionally, there are cases where maritime navigational accidents need proper rules and procedures.

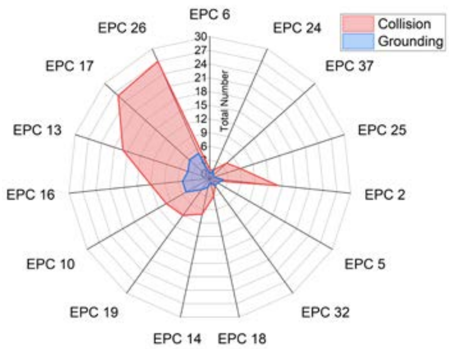

Figure 5. Management causal factors

3.3 *Quantitative Results*

3.3.1 *Determining the APE Value*

Tables 5 and 6 show the case numbers, EPC series, TOPSIS calculation values of APE, values λ max, consistency index (CI), and consistency ratio (CR). λmax is the maximum eigenvalue of the pairwise comparison matrix used to determine the weights of the criteria, which will utilised to calculate CI and CR. The Pairwise Comparison Matrix (PCM), which compares each criterion with all other criteria and assigns a relative weight to each criterion, has a better degree of consistency when the CI values are smaller. The CR value measures the consistency of PCM by comparing the CI with random index (RI) values. Greater matrix consistency was indicated by lower CR values.

Table 5. The results of TOPSIS calculation for each EPC on Collision accidents

Case	EPC Series	APE	λmax	CI	CR
1	EPC 26	0.253	8.6	0.09	0.061
	EPC 25	0.203			
	EPC 19	0.175			
	EPC 36	0.132			
	EPC 13	0.098			
	EPC 17	0.093			
	EPC 12	0.046			
	EPC 33	0.001			
2a	EPC 10	0.459	4.24	0.08	0.09
	EPC 12	0.269			
	EPC 23	0.262			
	EPC 33	0.011			
2b	EPC 36	0.327	5.21	0.05	0.047
	EPC 34	0.325			
	EPC 10	0.305			
	EPC 33	0.042			
	EPC 16	0.002			

In the table, the series of the EPC are arranged based on the highest APE number. The highest APE value indicates a leading factor that contributes to human error. Since the CR values are all below 0.1, it can be stated that the TOPSIS method for determining APE does not have discrepancies and inconsistencies.

Table 6. The results of TOPSIS calculation for each EPC on Grounding accidents

Case	EPC Series	APE	λmax	CI	CR
1	EPC 35	0.270	8.97	0.14	0.098
	EPC 26	0.230			
	EPC 22	0.145			
	EPC 12	0.112			
	EPC 10	0.089			
	EPC 17	0.076			
	EPC 16	0.076			
	EPC 33	0.001			
5	EPC 17	0.392	4.21	0.07	0.08
	EPC 26	0.325			
	EPC 10	0.189			
	EPC 33	0.093			

3.3.2 *Main causal factors*

The main causal factors in maritime navigational accidents are determined by the highest value of the Assessed Proportion Effect (APE) for each ship analysed and are composed of a series of Error Producing Conditions (EPC). Table 7 shows the distribution of the main causal factors, which differ from collision and grounding accidents. In navigational accidents, the most critical error is inadequate checking (EPC 17), followed by progress tracking lack (EPC 26) and unreliable instruments (EPC 23). The monitoring sub-factors, which include EPC 17 and EPC 26, are the main causes of accidents.

The main causal factors for collision and grounding accidents differ. EPC 23 is the main causal factor in most grounding accidents, while it occurs only once in collision accidents. Collision accidents have more EPCs as the main causal factors than grounding accidents. Management factors predominantly dominate the main causal factors for maritime navigational accidents. The management sub-factors identified as the main causal factors include monitoring, communication, coordination, and rules and procedures.

The remaining causal factors have varying values of APE, with some having high values for one type of accident but not the other. Some EPCs, such as EPC 7 and EPC 12, have a value of 3 for Collision but do not have any value for Grounding. Similarly, EPC 35 has a value of 1 for both types of accidents, while EPC 2 has a value of 1 only for Grounding.

Table 7. Number of occurrences of EPC as the highest APE for each ship

Highest APE for each ship	Navigational Accidents	
EPC - 4M	Collision	Grounding
Management-Monitoring (EPC 17 and EPC 26)	14	4
Management-Communication (EPC 10, EPC 13, EPC 14, EPC 16, EP 19)	13	3
Management-Coordination (EPC 24 and EPC 25)	4	1
Man-Physical (EPC 36)	3	-
Man-Experience (EPC 12)	3	-
Man-Skill and Knowledge (EPC 7)	3	-
Man-Psychological (EPC 21)	3	-
Man-Health (EPC 35)	1	1
Management-Rules and Procedures (EPC 32)	1	-
Media (EPC 33)	1	-
Machine (EPC 23)	1	6

In addition to the main causal factors, the analysis of maritime navigational accidents also recorded all contributing factors. The study found that all four factors, namely man, machine, media, and management, contribute to these accidents. The subsequent paragraph will elaborate on the findings of the contributing factors in the analysis of maritime navigational accidents.

3.3.3 *Calculate the AIV and HEP value*

Table 8 shows the example of the value of AIV and HEP from two collision accidents using Equation 2. The results show that in case 1, the probability of human error is 43.8%. Meanwhile, if human error is involved in two ships, the HEP is calculated particularly for each ship, as shown in case numbers 2a and 2b. The result shows that ship A has a probability of human error of 100% and ship B has 40.37%, which means that ship A has more influence on the accident due to adverse conditions of human operator conditions. If the value of the HEP calculation is more than 1, the value is rounded off to 1. For the grounding accident, Table 9 shows the HEP value for two example cases, cases 1 and 5, which are 6.21% and 7.56%, respectively, which indicates that in grounding accidents, the influence of human error is considerably lower than in collision accidents.

Figure 5 shows the distribution of HEP values for collision and Grounding to get an overview of the proportion of HEP values in accident cases, especially in navigational accidents. For collision accidents, it is evident that there is a total of 15 ships with an HEP of more than 75% and 12 ships with an HEP of more than 50%, which shows that the influence of human factors is paramount in contributing to the occurrence of accidents. In contrast, the influence of human error is insignificant in grounding accidents in Germany, with only three ships out of 15 with a HEP of more than 75%. The distinct difference can be caused by the high involvement of the machine failure in the grounding accidents where the value affects the APE value in the calculation of AIV and HEP.

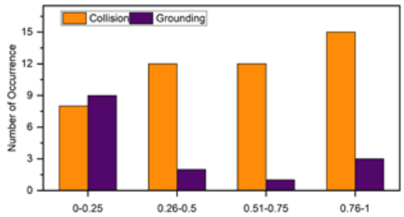

Figure 5. Human Error Probability (HEP) value distribution for Collision and Grounding

4 DISCUSSION AND CONSIDERATIONS

In the previous research by Bowo 2024 [30], collision accidents that occurred in Hong Kong were analysed using MAART. The research focused on the use of the MAART method. In this study, additional maritime navigational accidents that occurred in Germany were analysed using the same method [31]. This paper is a development of the previous research; by adding types of accidents other than ship collisions, the results show that management factors are not the main factor in grounding accidents. The novelty of this research lies in its detailed examination of the HEP result, which has been underexplored in previous studies. The MAART method categorises working situations that lead to accidents to determine their severity and novelty, which is important in characterising the situations that have a higher probability of accidents. The Error Producing Conditions (EPC) are then categorised into four main factors: man, machine, media, and management, which helps in understanding the main causal factors before delving into the detailed factors for the mitigation process. The MAART method also includes multi-criteria decision-making, such as TOPSIS, to make the calculation of the Human Error Probability (HEP) more objective.

Based on the results of the EPC, the management factor had the highest number of contributing factors to accidents, followed by media and machine factors. In this case, the management factor refers to bridge resource management (BRM), which is an effort to manage and maximise all resources on board (human and machine) to maintain the safe operation and passage of the ship [33]. Although there is an element of human error, the sub-factors of the management causal factor emphasise how the failure and disjointedness of the BRM on the ship contribute to accidents.

The EPC "Progress Tracking Lack" is the highest number of EPC followed by "Inadequate Checking" in monitoring causal factors. Progress tracking lack is the case when the OOW (Officer on Watch) does not frequently check the vessel tracking, and Inadequate checking is considered as the inability of the OOW to check vessel condition properly. Both cases are one of the main factors that caused the ship to deviate from the original track, leading to a collision and grounding[35].

To analyse the accident, the two mentioned failures occurred because of errors in conducting the BRM technique. For example, the planning failed when the master instructed to have two officers on standby during the watch hour, which did not comply with the ISM manual, and the master did not distribute the task among officers. Due to working overtime and not complying with STCW-2010[36], the officer experienced fatigue; consequently, the "Inadequate checking" cases occurred.

In addition, the crew must constantly monitor the condition or sensors on the ship. Good coordination between the bridge and ECR (Engine Control Room) needs to be implemented on this occasion. For example, an "Inadequate checking" happened when the ECR crew did not monitor the operation of the engine order that the master had telegraphed, which led to an engine failure and collision. From the previous case, it can also be concluded that the appropriate management system is not only applied on the bridge but also to maintain good coordination with another department to ensure the ship's safety.

Table 8. AIV and HEP Values for two cases in Collision accidents

		TOP								BODY									
No	GT	NHU	EPC	APE	EPC	APE	EPC	APE	EPC	APE	EPC	APE	EPC	APE	EPC	APE	EPC	APE	HEP
1	C	0.16	26	0.253	25	0.203	19	0.175	36	0.132	13	0.098	17	0.093	12	0.046	33	0.001	0.438
		AIV=1.101		AIV=1.122		AIV=1.262		AIV=1.008		AIV=1.294		AIV=1.186		AIV=1.137		AIV=1.000			
2a	C	0.16	10	0.459	12	0.269	23	0.262	33	0.011									1
		AIV=3.064		AIV=1.807		AIV=1.157		AIV=1.002											
2b	C	0.16	36	0.327	34	0.325	10	0.305	33	0.042	16	0.002							0.4037
		AIV=1.020		AIV=1.032		AIV=2.372		AIV=1.006		AIV=1.003									

Table 9. AIV and HEP Value for two cases in Grounding accidents

		TOP								BODY									
No	GT	NHU	EPC	APE	EPC	APE	EPC	APE	EPC	APE	EPC	APE	EPC	APE	EPC	APE	EPC	APE	HEP
1	E	0.02	35	0.27	26	0.23	22	0.145	12	0.112	10	0.089	17	0.076	16	0.076	33	0.001	0.0621
		AIV=1.027		AIV=1.092		AIV=1.116		AIV=1.337		AIV=1.399		AIV=1.152		AIV=1.151		AIV=1.000			
5	E	0.02	17	0.392	26	0.325	10	0.189	33	0.093									0.0756
		AIV=1.784		AIV=1.130		AIV=1.850		AIV=1.014											

Communication problems are one of the most frequent contributing factors to maritime accidents. Especially in a collision accident, the inter-ship communication problem led to a severe accident[37][38]. Since communication in maritime communication is related to the way to inform about the ongoing situation or condition regarding the vessel, there is a possibility that misinterpretation occurs. In the maritime sector, the lines of communication can be divided into Internal (inter-ship) and external (Ship to ship, ship to VTS)[39]. The inter-ship communication involves the interaction between crew members, crew and their captain, and captain and pilot. The problem that frequently arises within the bridge is the different mental models between the officer, captain, or pilot. Since they have different views about the situation, they sometimes do not communicate or share their thoughts for several reasons. This situation will not create a closed-loop communication, which will hinder successful communication on the bridge [40].

Communication problems that occur in maritime accidents can also be distinguished by type. This study is called the EPC. According to the EPC calculation, In Germany, the highest number of communication problems that occur from a collision accident is "Poor Feedback", while for the grounding accident, it is "Impoverished information" and "Knowledge Transfer." To maintain proper communication, the sender and the receivers are responsible for ensuring that all the information has been received clearly or maintaining closed-loop communication. In a "Poor Feedback" case, the receiver does not reply to the sender with adequate information, such as incomplete information regarding the position, language difficulties, or information different from the actual intention.

In grounding accidents, based on the results of the EPC, the machine factor had the highest number of contributing factors to accidents, followed by media and management. In this case, the failure of unreliable instruments had the highest number of EPCs. Specifically, issues such as faulty navigational aids, radar malfunctions, and defective communication systems were identified as primary contributors to these incidents. The prevalence of these technical failures underscores the critical need for robust and reliable instrumentation on board vessels.

The analysis revealed that outdated or poorly maintained instruments often failed at crucial moments, leading to unreliable instruments, navigational errors, and, ultimately, grounding incidents. These findings highlight the importance of regular maintenance and timely upgrades of navigational and communication equipment to ensure their reliability and effectiveness.

Additionally, the study pointed out that media factors, including poor environment, also played a significant role. This includes weather forecasts and maritime warnings that mislead the crew and hinder effective decision-making. The integration of real-time data and improved communication channels between vessels and maritime authorities were suggested as measures to mitigate these risks.

Management factors, while not the leading cause, still contributed notably to grounding accidents. Issues such as communication and coordination were commonly observed. The research advocates for enhanced training programs that emphasise the operation and troubleshooting of navigational instruments, as well as stricter adherence to maintenance schedules.

On the other hand, research conducted by Bowo [24] using the HEART method showed that the management factor had the highest number of contributing factors to grounding accidents, followed by communication, human, and machine. The different results show that the methodologies and contexts in which these studies were conducted might influence the outcomes. For instance, variations in data collection techniques, sample sizes, and specific circumstances of the accidents being analysed could lead to different conclusions about the primary contributing factors. Moreover, the emphasis on management factors in Bowo's study highlights the critical role that organisational and administrative practices play in ensuring maritime safety. This contrasts with this research that may focus more on technical aspects of grounding accidents. These discrepancies underscore the complexity of grounding accidents and suggest that a multifaceted approach, considering various factors and perspectives, is essential for a comprehensive understanding and effective prevention strategies.

Based on the classification of the EPC and TOPSIS calculation to estimate the APE, the HEP can be calculated for each ship. The analysis of the Human Error Probability (HEP) results for both collision and grounding accidents indicates some significant differences. The HEP values for collision accidents range from 0.06 to 1, with an average of 0.54. In contrast, the HEP values for grounding accidents range from 0.0048 to 1, with an average of 0.26.

The higher average HEP values for collision accidents suggest that human errors are more prevalent in such accidents. The most frequent HEP values for collision accidents range between 0.4 and 0.6, indicating that human error is present in almost half of all collisions. In contrast, the most frequent HEP values for grounding accidents range between 0.1 and 0.2, indicating that human error is present in about a quarter of all groundings.

Moreover, the HEP values for collision accidents show a wider range than those for grounding accidents, with some values as high as 1. This suggests that human errors can be a major contributor to the occurrence of collision accidents. On the other hand, the HEP values for grounding accidents are generally lower, with the highest value being 1, indicating that the occurrence of grounding accidents is less likely to be due to human error. However, it should be noted that there is a difference in the number of data used in the study between collision and grounding accidents, which could have an impact on the results. Nonetheless, the analysis of the HEP results suggests that human error is a significant factor in both collision and grounding accidents, but it is more prevalent in collision accidents.

For further studies, it is noted that the value of HEP does not represent the overall risk value. The probability value should be incorporated with the severity value of each accident. Incorporating the risk rating for each EPC within the accident as the quantified risk value could enhance the effectiveness of reducing the risk of maritime accidents.

5 CONCLUSIONS

In conclusion, this study added grounding as the additional maritime navigational accident that occurred in Germany using the MAART method. The novelty of this research lies in its detailed examination of the HEP result, which has been underexplored in previous studies. The analysis focused on identifying the causal factors, categorising them into four major factors (man, machine, media, and management), and examining their contributions to collision and grounding accidents as a navigational maritime accident by using the EPC-4M and TOPSIS method. The aim of this study is to identify what errors may occur in the human response to marine navigational accidents using MAART. This study used data on collisions and groundings in Germany from 2008 to 2020. A total of 48 reports and 62 vessels were analysed, with the limitation that only English reports were processed. The results highlight the significant role of management factors in influencing collision accidents, followed by man, media and machine factors. However, the data show notable differences in the Error Producing Condition and Generic Task Analysis involved in collision and grounding cases. On the other hand, in grounding accidents, based on the results of the EPC, the machine factor had the highest number of contributing factors to accidents, followed by media and management.

The novel approach in MAART methodology incorporates the TOPSIS methodology to generate APE that will be utilised to calculate the HEP for each ship. The TOPSIS methodology provides a more accurate value of APE rather than the general judgment from the users. The more precise value of APE will be instrumental in calculating the value of AIV and HEP for each EPC and ship in maritime navigational accidents. TOPSIS calculation shows that, for the collision accidents, the EPCs related to management have the highest occurrence of APE value for each accident and ship case 32 times out of 47. On the other hand, EPCs related to machines have the highest appearance, with six times out of 15. The results of APE correspond with the HEP results. Regarding collision accidents, 57% of the ships have more than 0.5 -1 probability of human error, which concluded that for collision cases, human error is solely the most dominant factor. For the grounding, only 4 of the ships out of 15 have more than 50% HEP, which indicates that machine factors also play important roles that can affect human error in operating the equipment or instruments.

By understanding the specific factors and estimating the pinpoint value of human error probability that contribute to navigational maritime accidents, this study provides valuable insights for the development of preventive measures and the enhancement of safety practices in the maritime industry. It highlights the significance of effective management, communication, monitoring, and adherence to procedures in minimising the risk of accidents and ensuring the safe navigation of vessels.

REFERENCES

[1] Fan L, Wang M, Yin J. The impacts of risk level based on PSC inspection deficiencies on ship accident consequences. Research in Transportation Business and Management. 2019;33:100464.

[2] Bowo LP, Mutmainnah W, Furusho M. The Development of Marine Accidents Human Reliability Assessment Approach: HEART Methodology and MOP Model. TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation. 2017;11:63–68.

[3] Li B, Pang FW. An approach of vessel collision risk assessment based on the D-S evidence theory. Ocean Engineering. 2013;74:16–21.

[4] Weng J, Yang D. Investigation of shipping accident injury severity and mortality. Accid Anal Prev. 2015;76:92–101.

[5] Weng J, Ge YE, Han H. Evaluation of Shipping Accident Casualties using Zero-inflated Negative Binomial Regression Technique. Journal of Navigation. 2016;69:433–448.

[6] Ko YG, Kim SJ, Paik JK. Effects of a deformable striking ship's bow on the structural crashworthiness in ship–ship collisions. Ships and Offshore Structures. 2018;13:228–250.

[7] Kim K Il, Jeong JS, Lee BG. Study on the analysis of near-miss ship collisions using logistic regression. Journal of Advanced Computational Intelligence and Intelligent Informatics. 2017;21:467–473.

[8] Du L, Goerlandt F, Kujala P. Review and analysis of methods for assessing maritime waterway risk based on non-accident critical events detected from AIS data. Reliab Eng Syst Saf. 2020;200:106933.

[9] Pedersen PT, Chen J, Zhu L. Design of bridges against ship collisions. Marine Structures. 2020;74:102810.

[10] Chen J, Bian W, Wan Z, et al. Identifying factors influencing total-loss marine accidents in the world: Analysis and evaluation based on ship types and sea regions. Ocean Engineering. 2019;191:106495.

[11] Chen J, Bian W, Wan Z, et al. Factor assessment of marine casualties caused by total loss. International Journal of Disaster Risk Reduction. 2020;47:101560.

[12] Kim K Il, Jeong JS, Lee BG. Study on the analysis of near-miss ship collisions using logistic regression. Journal of Advanced Computational Intelligence and Intelligent Informatics. 2017;21:467–473.

[13] Wang Y, Fu S. Framework for Process Analysis of Maritime Accidents Caused by the Unsafe Acts of Seafarers: A Case Study of Ship Collision. J Mar Sci Eng. 2022;10:1793.

[14] Sujan MA, Embrey D, Huang H. On the application of Human Reliability Analysis in healthcare: Opportunities and challenges. Reliab Eng Syst Saf. 2020;194:0–1.

[15] Helmreich RL. On error management: Lessons from aviation. Br Med J. 2000;320:781–785.

[16] Kirimoto Y, Hirotsu Y, Nonose K, et al. Development of a human reliability analysis (HRA) guide for qualitative analysis with emphasis on narratives and models for tasks in extreme conditions. Nuclear Engineering and Technology. 2021;53:376–385.

[17] Mirzaei Aliabadi M, Esmaeili R, Mohammadfam I, et al. Human Reliability Analysis (HRA) Using Standardized Plant Analysis Risk-Human (SPAR-H) and Bayesian Network (BN) for Pipeline Inspection Gauges (PIG) Operation: A Case Study in a Gas Transmission Plant. Health Scope. 2019;8.

[18] Di Pasquale V, Miranda S, Iannone R, et al. A Simulator for Human Error Probability Analysis (SHERPA). Reliab

Eng Syst Saf [Internet]. 2015;139:17–32. Available from: https://www.sciencedirect.com/science/article/pii/S0951832015000484.
[19] Ramezani A, Nazari T, Rabiee A, et al. Human error probability quantification for NPP post-accident analysis using Cognitive-Based THERP method. Progress in Nuclear Energy. 2020;123:103281.
[20] Gibson WH, Kirwan B. Application of the CARA HRA tool to air traffic management safety cases. 9th International Conference on Probabilistic Safety Assessment and Management 2008, PSAM 2008. 2008;2:1312–1319.
[21] 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.
[22] Deacon T, Amyotte PR, Khan FI, et al. A framework for human error analysis of offshore evacuations. Saf Sci. 2013;51:319–327.
[23] 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.
[24] Bowo LP, Furusho M. A comparison of the common causes of maritime accidents in Canada, Indonesia, Japan, Australia, and England. Advances in Intelligent Systems and Computing. Springer International Publishing; 2019.
[25] Islam R, Abbassi R, Garaniya V, et al. Development of a human reliability assessment technique for the maintenance procedures of marine and offshore operations. J Loss Prev Process Ind. 2017;50:416–428.
[26] 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.
[27] De Maya BN, Kurt RE. Application of fuzzy cognitive maps to investigate the contributors of maritime grounding accidents. RINA, Royal Institution of Naval Architects - Human Factors 2018, Papers. 2018;44.
[28] 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.
[29] Bowo LP, Prilana RE, Furusho M. A modified heart-4m method with topsis for analyzing Indonesia collision accidents. TransNav. 2020;14:751–759.
[30] Bowo LP, Ispandiari AR, Wibowo DA, et al. Maritime accident analysis and reduction technique for analysing maritime collision accidents. Australian Journal of Maritime and Ocean Affairs [Internet]. 2024;0:1–28. Available from: https://doi.org/10.1080/18366503.2024.2350792.
[31] Mazaheri A, Montewka J, Kujala P. Correlation between the Ship Grounding Accident and the Ship Traffic – A Case Study Based on the Statistics of the Gulf of Finland. TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation. 2013;7:119–124.
[32] Mazaheri A, Montewka J, Nisula J, et al. Usability of accident and incident reports for evidence-based risk modeling – A case study on ship grounding reports. Saf Sci. 2015;76:202–214.
[33] Bowo LP. A NEW METHODOLOGY ON HUMAN RELIABILITY ANALYSIS FOR SHIP SAFETY: Maritime Accident Analysis and Reduction Technique (MAART). Kobe University; 2021.
[34] Bowo LP, Furusho M. Integrated methods for analysing the causal factors in Australian maritime occupational accidents. Int J Human Factors and Ergonomics. 2021;8:23–25.
[35] Kamis AS, Fuad AFA, Anwar AQ, et al. A systematic scoping review on ship accidents due to off-track manoeuvring: A systematic scoping review on ship accidents due to off-track manoeuvring. WMU Journal of Maritime Affairs. Springer Berlin Heidelberg; 2022.
[36] ITF. STCW: A Guide for Seafarers: Taking into account the 2010 Manila amendments. International Transport Workers' Federation,. 2010;78p.
[37] Chauvin C, Lardjane S, Morel G, et al. Human and organisational factors in maritime accidents: Analysis of collisions at sea using the HFACS. Accid Anal Prev. 2013;59:26–37.
[38] Kamis AS, Fuad AFA, Saadon MSI, et al. the Impact of Basic Training on Seafarers' Safety Knowledge, Attitude and Behaviour. J Sustain Sci Manag. 2020;15:137–158.
[39] Parrott DS. Bridge Resource Management for Small Ships: The Watchkeeper's Manual for Limited-tonnage Vessels. McGraw Hill Professional; 2011.
[40] Salas E, Rosen MA, Burke CS, et al. Markers for enhancing team cognition in complex environments: The power of team performance diagnosis. Aviat Space Environ Med. 2007;78.