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Usability of Human Error Assessment and Reduction Technique with a 4M framework (HEART–4M) – A Case Study on Ship Grounding Accidents

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Abstract

Human error plays a vital role in causing maritime accidents. This paper presents the analysis of human factors in 52 grounding accident reports of ships greater than 10,000 GT retrieved from 11 national investigation boards. In this study, the categorization of error-producing conditions (EPCs) from the Human Error Assessment and Reduction Technique (HEART) methodology to 4M (Man, Machine, Media, and Management) framework, EPC–4M was carried out. This study aims to categorize the EPCs to the 4M framework to better explain these other factors that relate to human factors. There were 18 EPCs in man factors, 3 EPCs in machine factors, 1 EPC in media factors, and 16 EPCs in management factors. Three types of generic tasks were obtained in this grounding analysis, and 259 relevance EPC–4M were acquired. EPCs related to management factors were the primary causes of such accidents. The average human error probability for these cases was around 55%.

Keywords: *EPC – 4M, HEART methodology, 4M framework, Grounding, Human error.*

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1. Introduction

An accident, result of an unintended or unexpected occurrence can cause economic and noneconomic damage to a human, an object, or the environment [1, 2]. Statistics on casualties within the maritime context show that human error is one of the most critical causal factors. About 70% of maritime accidents for onboard operations are accounted for by human errors [3]. However, poor design factors, such as; problems with equipment, maintenance, working space layout, stress faced by the operator involving unreliable work tools, fatigue and environmental factors also contribute to the occurrence of errors [4, 5, 6].

Human reliability assessment (HRA) has become essential in the industry and is a growing field of concern for the public and regulators [7]. HRA is more than quantification, and it requires in-depth analysis to analyze tasks and identify errors, and to reduce the impact of errors if needed [8]. The Human Error Assessment and Reduction Technique (HEART) methodology is a form of HRA that was established by Williams in 1986 to analyze nuclear power plant accidents [9]. However, HEART methodology can be used in other industries as well because it is quite flexible and easy to utilize. The other implementations of HEART methodology are in aviation [10], railway [11], offshore drilling [7], and maritime operations [11, 12]. HEART methodology has been applied as well as to assess the maritime accidents, such as collision, sinking, fire/explosion, occupational accident and contact accident [14], yet, the application of the HEART method is still needed development to be more suitable in the maritime accident. Because the Error Producing Condition (EPC) in the HEART method need to be categorized in order to clarify the group of each EPC based on the work environment in the maritime industry.

Nevertheless, IMO has developed guidelines to categorize the causal factors for investigating and analyzing maritime accidents and incidents by considering not only human but also organizational factors [15]. The research associate human, systemic, and organizational failures have been developed by many researchers; the most well-known frameworks are the SHEL model by Hawkins [16], which considers Software (S), Hardware (H), Environment (E) and Liveware (L), and the 4M framework (Man, Machine, Media, and Management) [17].

This study aims to find the causal factors relative to machine, media, and management factors that may influence the human condition and performance, particularly for the bridge team. It also aims to investigate the potential navigational likelihood of ship grounding by proposing a hybrid maritime accident analysis to enhance safety at sea.

2. Grounding Accident Reports as Data Source

Accident reports are commonly used as data sources for several types of research involving maritime accident analysis. Accident reports are designated as secondary data sources because they are created from primary data sources by interviewing the operators and analyzing first-hand information obtained by the accident investigator after the accident [16, 17]. Official maritime accident reports are prepared by national investigation boards and provide valuable information regarding the occurrence of the accident. The accidents reports investigated in the current study were retrieved from the national investigation boards as follow: Accident Investigation Board Norway (AIBN) 3 cases, Australian Transport Safety Bureau (ATSB) 8 cases, Federal Bureau of Maritime Casualty Investigation (BSU) 6 cases, Danish Maritime Accident

Investigation Board (DMAIB) 3 cases, Japan Transport Safety Board (JTSB) 2 cases, Marine Accident Investigation Branch (MAIB) 8 cases, United States National Transportation Safety Board (NTSB) 3 cases, National Transportation Safety Committee (NTSC) 1 cases, Safety Investigation Authority (SIA) 4 cases, Transport Accident Investigation Commission (TAIC) 4 cases, and Transportation Safety Board of Canada (TSB) 10 cases.

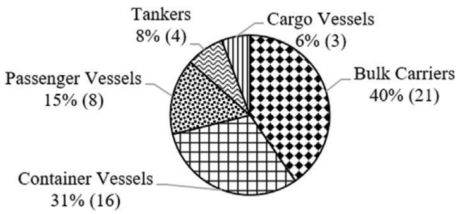

Figure 1. *Types of Ships Considered in the Analysis*

This study obtained information on 52 grounding accidents that occurred between 2007 and 2017 from publicly available maritime accident investigation reports. The availability of the reports varied in each country. The accidents involved ships with gross tonnages of more than 10,000 GT; therefore, fishing vessels / boats were not included in this analysis. Among the analyzed accidents, 31 ships suffered extensive damage. Thirteen cases of grounding occurred in windy situations measuring 6–12 on the Beaufort wind scale. The types of ships involved in the accidents are shown in Figure 1. The majority of ship types analyzed were bulk carriers, followed by container ships, passenger ships, tanker ships, and cargo ships.

The sections of accident reports that were thoroughly reviewed for this study were the synopses, analysis sections, and the conclusions. All the information from the accident report has to be derived before it can be used. However, derivation of the information typically requires human effort; thus, the risk of human subjectivity exists [19]. To minimize human subjectivity, the reviewers of the accident reports extracted the embedded information based only on the words that were written in the reports, avoiding further investigation and assumptions that could create subjective

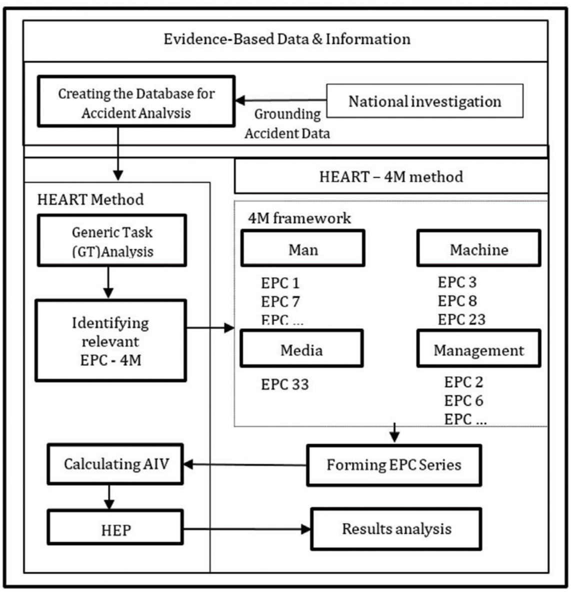

Figure 2. *Overview of HEART–4M Method*

opinions. The reports were all reviewed by researchers who are experts in the field of human factor and risk analysis.

3. HEART – 4M Method

This study proposes a hybrid methodology to evaluate human error by integrating HEART–4M method, it comprises four definitions for the HEART method's EPCs. Figure 2 presents an overview of this methodology.

Evidence-based data and information

A systematic accident database was generated in Microsoft Excel by tabulating the accident data into a textual format. The information in the database included the following information: Accident date and year, time of the accident, accident location, name of the ship involved, type of ship, technical specifications of the ship (gross tonnage, deadweight total), weather and environmental information at the time of occurrence, accident severity, as well as the number of fatalities/injuries, environmental damage, ship damage, accident causes.

Generic task classification

After extracting the data information from the maritime accident reports, we then applied the HEART–4M method. The first stage was the qualitative stage, in which the generic task was obtained and a Nominal Human Unreliability (NHU) value was assigned. By assigning the generic task, the researcher can determine whether the accident occurred as the result of a difficult task that needs a lot of concentration and specialized skill to do, or whether it occurred as a result of daily routine activities that the seafarer is already familiar with. The more frequent and more accessible the work carried on by the seafarers, the lower the NHU. Because the tasks are not typically the same, the researcher had to decide how to define the task and classify it accordingly [20].

Nine generic tasks were used in this study. Each generic task had an NHU between the 5th and 95th percentiles as lower and upper probability boundaries, respectively [20]. The applicability of the proposed NHU is based on the experience of the researchers, but Williams [9] provided a mean number to use if the assessor is unable to determine the exact number of the proposed NHU to analyze the task. The average NHU number is used in the Human Error Probability (HEP) calculation. The influence of weather and traffic conditions on the working situation onboard is also considered.

Table 1. *Generic Tasks (GT)*

Generic Tasks (GT)			
Code	**Type of work**	**Condition**	**NHU**
A	Totally unfamiliar	Works performed at speed with no real idea of likely consequences.	0.55
B	Restore the system to an original state on a single attempt	Doing it without supervision or procedures.	0.26
C	Complex task	Task requires a high level of comprehension and skill.	0.16
D	A fairly simple task	Works performed rapidly or given scant attention.	0.09
E	The routine, highly practiced, rapid task	Works involving a relatively low level of skill.	0.02

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Table 1. *Generic Tasks (GT) (Cont')*

Generic Tasks (GT)			
Code	**Type of work**	**Condition**	**NHU**
F	Restore a system to original	An error occurred even though following procedures with some checking.	0.003
G	Entirely familiar, highly practiced, routine task occurring several times per hour, performed to highest possible standards by a highly motivated, highly trained, and experienced person, totally aware of implications of failure, with time to correct the potential error	However, without the benefit of significant job aids.	0.0004
H	Respond correctly to the system command	Even when there is an augmented or automated supervisory system providing an accurate interpretation of the system stage.	0.00002
M	The miscellaneous task for which no description can be found.		0.03

If the weather and ship traffic conditions are deteriorating, a simple routine task could become a complicated task because of the totally unfamiliar conditions. The generic task information in Table 1 consists of generic task code, type of work, working conditions, and the NHU used in the HEP calculation. Here, the descriptions of generic tasks are different from generic tasks in general because there is a lengthy explanation of the generic task, divided into the type of work and the working conditions. This division can make it easier to determine which generic task is most suitable for the situation being investigated.

Classification of factors within the HEART–4M method

Based on the analysis and categorization of human factors that are represented by EPCs, the HEART–4M method was developed for the comprehensible categorization of factors responsible for maritime accidents. In the table, there are 4M factors—man, machine, media, and management factors—following by the EPCs that relate to each 4M factor.

Man factors

Human error is reported to be a significant factor for maritime accidents [21]. Human fatigue and task omission are closely related to failures of situational awareness [22]. Man factors are defined as all human elements that affect human behavior and performance while performing tasks. The man factors have some subfactors as shown in Table 2 as follows:

Table 2. *EPC – 4M, Man Factors*

Man factors		
1. Experience		
EPC 1	Unfamiliarity	Unfamiliarity with a situation which is potentially significant, but occurs infrequently, or which is novel
EPC 12	Misperception of risk	Misperception of an object, threat, or situation creates an unsafe situation
EPC 22	Lack of experience	Little opportunity to carry out the work

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Table 2. *EPC – 4M, Man Factors (Cont')*

2. Skill and Knowledge		
EPC 7	Irreversibility	No means of doing an unintended action
EPC 9	Technique unlearning	A need to learn a technique to support work
EPC 11	Performance ambiguity	Ambiguity in the required performance standards
EPC 15	Operator inexperience	A newly qualified seafarer
EPC 20	Educational mismatch	A mismatch between the educational achievement level and the requirements of the task
3. Psychological		
EPC 21	Dangerous incentives	An incentive to use dangerous procedures
EPC 28	Low meaning	Individual shows little or no intrinsic meaning in the work
EPC 29	Emotional stress	High level of emotional stress
EPC 31	Low morale	Individual shows low workforce morale
EPC 34	Low mental workload	Prolonged inactivity or highly repetitious cycling
4. Physical		
EPC 27	Physical capabilities	Working beyond physical capabilities that may cause danger
EPC 36	Task pacing	Unfocused and ineffective working situation due to lack of human resources and intervention of others
EPC 38	Age	Age of personnel performing perceptual works
5. Health		
EPC 30	Ill-health	Evidence of ill-health, fever, stomachache
EPC 35	Sleep cycle disruption	Disruption of normal work-sleep cycles

Table 3. *EPC – 4M, Machine Factors*

Machine factors		
EPC 3	Low signal-noise ratio	A low signal to noise ratio
EPC 8	Channel overload	A channel capacity overload, particularly one caused by simultaneous presentation of non-redundant information
EPC 23	Unreliable instruments	The unreliable instrument, machinery, and technology to support the work

Machine factors

Machine factors include the equipment, machinery, instruments, and facilities that support humans to perform their tasks correctly and satisfactorily. Table 3 shows the EPC that include in the machine factors.

Management factors

The International Safety Management (ISM) Code has addressed the influence of management in maritime accidents [24]. In the early 1990s, Bridge Resource Management (BRM) was adopted in the maritime industry as a safety and error management tool. According to the International Convention on Standards of Training, Certification, and Watchkeeping for Seafarers (the STCW Convention) in 2010, Reg. A-II/1. The details of EPC in the management factors are shown in Table 4 below.

***Table 4.** EPC – 4M, Management Factors*

Management factors		
1. Coordination		
EPC 2	Time shortage	A shortage of time available for error detection and correction
EPC 6	Model mismatch	A mismatch between a seafarer's model and that imagined by the designer
EPC 24	Absolute judgments required	A necessity for absolute judgments, which are beyond the capabilities or experience of an operator
EPC 25	Unclear allocation of function	Obscurity in allocating function and responsibility
EPC 37	Supernumeraries/ lack of human resources	Additional team members over or lack of team member, those necessary to perform the task regularly and satisfactorily
2. Rules and procedures		
EPC 4	Features over-ride allowed	A means of overriding information or features
EPC 5	Spatial and functional incompatibility	No means of conveying spatial and functional information to seafarer in a form which they can readily assimilate
EPC 32	Inconsistency of displays	Inconsistency meaning of procedures
3. Communication		
EPC 10	Knowledge transfer	The need to transfer specific or essential information from task to task without loss
EPC 13	Poor feedback	Ambiguous system feedback, language barrier
EPC 14	Delayed/incomplete feedback	No explicit direct and timely confirmation of an intended action from the portion of the system over which control is to be exerted
EPC 16	Impoverished information	Inadequate quality of information conveyed by procedures and person–person interaction
EPC 18	Objectives conflict	A conflict between immediate and long-term objectives
EPC 19	No diversity of information	No diversity of information input for veracity checks
4. Monitoring		
EPC 17	Inadequate checking	Little or no independent checking of output
EPC 26	Progress tracking lack	No effort to keep track of progress during the work

Media factors

Environmental conditions can be a significant factor in the occurrence of an accident [23]. The natural environment is the natural condition faced by the ship during her voyages, such as weather, wind, fog, tide, and all-natural conditions that can significantly affect ship stability and maneuverability and the ability of the bridge team to control the ship. The EPC included in media factors is EPC 33 poor environment.

4. Results

Generic task

The first step of HEART–4M is obtaining a suitable generic task. From the 52 cases of grounding accident reports that were analyzed, the most common generic task found was E, for routine, highly practiced, and rapid tasks that involve a relatively low level of skill. There were 21 cases included in the type E generic task.

Moreover, 16 cases involved fairly simple tasks performed rapidly or given scant attention, and 15 cases included complex tasks requiring a high level of comprehension and skill. The most frequent working situation on the bridge was the lack of maintaining the watch because of improper communication and coordination among bridge teams. Watchkeeping is a routine task. Nevertheless, if there are other obstacles during the task, it can become more difficult and complicated. Those obstacles include weather conditions and the traffic situation.

EPC – 4M

In this study, there were 259 EPC–4M factors found as causal factors in the 52 grounding accidents. Man factors had 68 EPCs. In man factors, 25 cases had a misperception of risk as one of the causal factors. There were five subfactors in the man factors obtained in the analysis: physical limitations, psychological limitations, experience, skill and knowledge, and health.

Management factors had the most EPCs, 160, whereas communication subfactors were the most numerous among other subfactors in the management factors. Knowledge transfer (EPC 10) is the most common EPC that causing grounding accidents, where about 33 cases have it as the causal factor. Moreover, impoverished information delivered during the watchkeeping situation also influences mistakes in decision making and appropriate actions to avoid accidents. There were three other subfactors among the management factors that influenced accidents: coordination, monitoring, and procedures.

Sixteen cases had instruments or machinery problems while sailing, which led to dangerous situations. The failure condition of the instrument and machinery factors was not communicated well among the seafarers on the bridge and engine room crews. Therefore, it leads to an incorrect perception of the decision-making of the ship maneuver by the bridge team.

There were 15 cases that were analyzed to have a poor environment EPC. The poor environment made the ships more challenging to maintain and to monitor due to strong winds (6 to 12 Beaufort) for 13 cases and because of high-density fog for 2 cases, which caused reduced visibility. The list of EPCs found in the analyses is presented in Table 5.

Table 5. *EPC–4M Results in Grounding Accidents*

Man Factors		**Total**	**Management Factors**		**Total**
Physical			*Communication*		
EPC 27	Physical capabilities	1	EPC 10	Knowledge transfer	33
EPC 36	Task pacing	5	EPC 13	Poor feedback	11
Psychological			EPC 14	Delayed/incomplete feedback	3
EPC 21	Dangerous incentives	4	EPC 16	Impoverished information	27
EPC 28	Low meaning	3	EPC 18	Objectives conflict	2
EPC 31	Low morale	1	EPC 19	No diversity of information	7
EPC 34	Low mental workload	3	*Coordination*		
Experience			EPC 2	Time shortage	3
EPC 1	Unfamiliarity	1	EPC 24	Absolute judgments required	4
EPC 12	Misperception of risk	25	EPC 25	Unclear allocation of function	1
EPC 22	Lack of experience	9	*Monitoring*		

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Table 5. *EPC–4M Results in Grounding Accidents (Cont')*

Man Factors		**Total**	**Management Factors**		**Total**
Skill and Knowledge			EPC 17	Inadequate Checking	29
EPC 7	Irreversibility	2	EPC 26	Progress tracking lack	29
EPC 9	Technique unlearning	1	*Procedures*		
EPC 11	Performance ambiguity	7	EPC 4	Features over-ride allowed	1
Health			EPC 5	Spatial and functional incompatibility	7
EPC 35	Sleep cycles disruption	6	EPC 32	Inconsistency of displays	3
Machine Factors			**Media Factors**		
EPC 23	Unreliable instruments	16	EPC 33	Poor environment	15

Table 6. *EPC Series*

No.	**Year**	**Date**	**Time**	**Top**	**Body**				
				EPC	**EPC**	**EPC**	**EPC**	**EPC**	**EPC**
1	2007	26-Feb	0:01	EPC22	EPC21	EPC18			
2		14-May	18:16	EPC10	EPC26	EPC16	EPC14		
...									
51	2017	9-Feb	5:55	EPC10	EPC22	EPC33	EPC16	EPC19	EPC26
52		10-Feb	18:17	EPC36	EPC17	EPC26			

EPC series

The EPC series, as shown in Table 6, aims to know more about the flow of events and which EPC has the highest APE weight. Those which selected as the Top of EPC series, have a significant effect on the accident. From the 259 EPC selected, 14 were categorized as the top of the EPC series. The most common top EPC was EPC 10 for knowledge transfer.

From the EPCs selected, 75% of the top EPCs were management factors, whereas 19% and 6% were man factors and machine factors, respectively. From the management factors, the EPCs related most to the communication subfactor were the most common factors leading to accidents. Those EPCs were EPC 10, EPC 16, EPC 13, and EPC 19, followed by the monitoring subfactor and procedures subfactors. Moreover, among the man factors, there were three subfactors selected: the experience subfactor, the psychological subfactor, and the physical subfactor. The number of EPC in each case varies, depending on the number of findings obtained, which is also related to the complexity of the case.

Human Error Probability (HEP)

In Table 7, there are examples of cases 1 and 2 HEP calculations. Table 7 provides the cases number, GT, NHU, selected EPC, assigned APE, the result of AIV and HEP. The explanation about assigning the GT and NHU has been explained in section 3, whereas GT chosen is due to the working condition of the seafarer at the time of the accidents and also considered the environmental condition. For more difficult tasks and conditions, the GT will be different and will have a more significant value of NHU. To assign the weight of APE for each EPC is based on the subjective judgment of the expert, more significant factor will

***Table 7.** HEP Calculation*

No.	GT	NHU	TOP		BODY						HEP
			EPC	APE	EPC	APE	EPC	APE	EPC	APE	
1	C	0.16	22	0.45	21	0.35	18	0.2			3.82E-01
			AIV = 1.36		AIV = 1.35		AIV = 1.3		AIV = 0		
2	D	0.09	10	0.5	26	0.3	16	0.15	14	0.05	4.68E-01
			AIV = 3.25		AIV = 1.12		AIV = 1.3		AIV = 1.1		

have higher weight of APE. After assigning the APE, equation (1) and (2) are used to calculate the AIV and HEP respectively.

Figure 3 displays all HEP values for grounding accidents. The HEP results might be affected by the selection of GT and also the number of EPCs chosen. Seventeen cases have HEP calculation results 1. In Figure 3, the gray line is the average HEP value in these cases. The average number is 55%. Seventeen cases had 100% human error involvement.

5. Discussion

Grounding analysis results

The analysis of the reviewed accident reports shows that the usability of maritime accident reports is reliable for extracting critical factors that influence the occurrence of accidents. The results of the GT in section 4 show that routine, highly practiced, and rapid tasks involving a relatively low level of skill were the task conditions when the accidents occurred, meaning that the seafarer had previously experienced this situation several times. However, they had become overconfident and tended to underestimate the task because they thought that they were familiar with the situation. This condition is similar to fairly simple tasks, in which seafarers perform the task rapidly or give it scant attention. Environmental conditions affected the human ability to address the situation in order to avoid an accident, but because of several other influential factors, the accident still occurred. With 15 out to 52 grounding cases that analyzed accidents occurred due to poor environment, the root cause of this situation is a misperception of the bridge team of the effect of the poor environment on the ship.

Based on the top-most EPC series, this study found that most causes recognized by investigators are management factors in terms of improper communication, monitoring, and lack of guideline procedures on the bridge, such as the

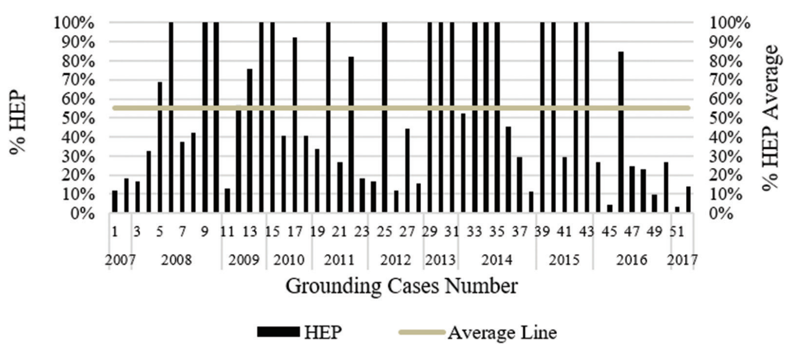

***Figure 3.** Human Error Probability Calculation Results*

bridge team being reluctant to provide information to the master because they felt they had less experience and knowledge than the master. Established incorrect practices such as categorizing piloting as a one-person duty were also a factor. Because of overconfidence in their knowledge and maneuvering skills, beyond that displayed by the bridge team, seafarers did not fully pay attention to watchkeeping. The lack of procedural information from companies regarding cooperation and communication in different conditions and a lack of knowledge transfer between the bridge team and the engine control room about engine failure conditions were other factors. In the future, since the application of automation ship will be done, the probability of man and management factors as the leading cause of the maritime accidents might be decreased, due to the less human power needed in the ship operation. However, it might increase EPC in machine factors.

The result of HEP from 2007 to 2017 is showing the decreasing trend, which means that improvements designed to decrease human error in maritime accidents were quite effective. This is in line with the post period of ISM code implementation, resulting in a significant reduction of human-induced factors in maritime accidents [25]. Improvement of the maritime technology, technology in shipbuilding and ship management and also better crew training, induce the improvement of maritime society [26]. The results for HEP were varied and depended on the selected GT, i.e., at the time of the accidents, what kind of situation existed, and which task was being performed. The more complex and challenging the task, the higher the NHU will be. Also, the number of EPCs selected in a case can influence the HEP results.

The advantages of the HEART – 4M method

Other factors related to humans can also influence human performance and judgment while performing their tasks, especially in terms of BRM. Machine factors, media factors, and management factors also strongly influence the human condition and performance [15], [17], [21]. The EPC factors established by William [9] also include some that are related to 4M (man, machine, media, and management) factors; yet, this method is still general. This study combines the HEART method, which was developed for assessing nuclear power plants, with 4M factors in order to understand the relation of 4M within the context of EPCs, particularly BRM. Previously, the conventional HEART method has been utilized to assess HEPs in maritime accident cases; yet, this method may have some weaknesses when selecting the EPCs and determining the mitigation process because it is still general. There are no classification details yet in the HEART method EPCs. Nevertheless, in the BRM, machinery, environment, and management factors can strongly influence human performance. Therefore, in this study, EPCs were classified into 4M to clarify the role of these other factors.

Finally, a hybrid method of HEART–4M is proposed, which was applied to evaluate the HEP in maritime accidents, particularly in grounding accidents. The integration of the frameworks suggests the relation of each factor and which EPC should belong in the 4M factors. It can be argued that by using the integrated method presented in this paper as a complement to a HEART method, the problem about the relationships between factors and the involvement of other factors in maritime accidents is now well addressed. At least two advantages can be obtained from the proposed method:

1. It can reveal the causality among the different factors in terms of EPC–4M classification, which focused on the origins of the causal factors. For example, if the report stated that the coordination of the bridge team was defective, we could study this in more detail by looking to EPC–4M in the coordination subfactor.
2. It provides information for identifying human factors and other factors that affect human behavior.
3. It provides accident assessors with the knowledge of which factors have the highest impact on accidents because of the performance of the EPC series. Moreover, it is easy for assessors to determine mitigation actions to reduce the value of errors that have occurred or may occur in the future.

6. Conclusion

A version of HEART–4M method was introduced using grounding accident reports, and the concept of the influence of other factors related to human factors, i.e., machine, media, and management factors, in maritime accidents were used to analyze the accident reports. Accident reports are concluded to be a reliable source of evidence data to extract information about the most critical factors. A total of 52 grounding accident reports were retrieved from 11 national investigation boards for the period 2007–2017, and these were analyzed using the HEART–4M method. There were 259 EPC–4M factors found as causal factors, where management factors were the most common factors found and the most common top of EPC series. The average HEP number calculated was 55%, and HEP trends were seen to be decreasing. Moreover, the applicability of the HEART–4M method provides a better explanation of which factors require attention rather than classifying causes as exclusively human factors.

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