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# A Modified HEART – 4M Method with TOPSIS for Analyzing Indonesia Collision Accidents

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ABSTRACT: Human error is recognized as the most common factor that causes maritime accidents. The human error assessment and reduction technique (HEART) is a human reliability assessment (HRA) that has been widely applied in various industries. Furthermore, the HEART – 4M method has been proposed to assess maritime accidents. The HEART – 4M method can clearly define the relationship between man, machine, media, and management factors and the human error. However, the calculation process to determine the weight of every selected error-producing condition (EPC) suffers from the uncertainty of the assessor's estimation in practical applications, which may affect the objectivity of its result. In this study, a modification of the HEART – 4M method with the technique for order preference by similarity to ideal solution (TOPSIS) is proposed. TOPSIS is a multi-criteria decision making (MCDM) tool. This study aims to develop the HEART – 4M method to make it more comprehensive and objective when assessing maritime accidents. First, the parameter of the generic task is determined as in the conventional HEART method. Second, the causal factors are converted to the suitable EPC – 4M, and there are four classification factors for the 38 standard EPCs, which are divided into man, machine, media, and management factors. Third, the TOPSIS is applied to handle the problems of interdependencies and interaction among EPC – 4M and the uncertainty that exists in the assessor´s judgment. The proportion effect of each EPC – 4M is determined through TOPSIS by considering the correlation among EPC – 4M. Finally, thirteen collision data obtained from the National Transportation and Safety Committee of Indonesia are assessed to apply the proposed method.

## 1 INTRODUCTION

The International Maritime Organization (IMO), the International Labour Organization (ILO), the Ship Classification Societies (IACS), and the implementation of the 1998 ISM Code 1998, as an international standard for the safe operation of ships and the advances in technology, have issued many rules and standards concerning human errors. After their implementation, the number of human errors in maritime accidents was significantly reduced (Akyuz, Celik, and Cebi 2016; Hetherington, Flin, and Mearns 2006; Lee and Chung 2018; Tzannatos and Kokotos 2009). Nevertheless, despite the continuous improvement, it is still found that human error influences maritime accidents (Bowo and Furusho 2019b; Kokotos and Linardatos 2011). According to the European Maritime Safety Agency (EMSA), human actions are the most common factor contributing to maritime accidents, accounting for approximately 66% of the total of 4104 accidents analyzed (EMSA 2019). Moreover, it is also supported by other studies that the percentage of human error involved in maritime accidents is 80% (Graziano, Teixeira, and Guedes Soares 2016; Soares and Teixeira 2001; Sotiralis et al. 2016).

Besides, the human error is recognized as the predominant cause not only in maritime accidents but also in many other domains, such as railway transportation (Gibson et al. 2013; Wang, Liu, and Qin 2018a), nuclear power plants (Park, Arigi, and Kim 2019), aviation (Kirwan and Gibson 2009), and healthcare services (Castiglia, Giardina, and Tomarchio 2015). Thus, numerous researchers and practitioners have developed alternative models and theories related to the human reliability analysis (HRA) (Akyuz et al. 2016; Bowo, Mutmainnah, and Furusho 2017; Dsouza and Lu 2017; Wang et al. 2018a). The HRA has three purposes: identification of human errors, prediction of future risk probability, and reduction of this probability (Kirwan 1996). The development of HRA comprises three different generations (Wang, Liu, and Qin 2018b). In the first generation, in the 1980s, the HRA was developed to predict and calculate the probability of human error, and it focused on the skill and rule base level of human action. The first generation included the following methodologies: technique for human error rate prediction (THERP), accident sequence evaluation program (ASEP), human error assessment and reduction technique (HEART), and simplified plant analysis risk Human reliability assessment (SPAR-H). The second-generation methodologies considered the influence of internal and external contexts on the error and the cognitive context that may influence the system operation. A technique for human event analysis (ATHEANA) and the cognitive reliability and error analysis method (CREAM) were included in the second generation. Finally, the third generation, which includes the present method and the developments from previous generations, aims at being more suitable for particular industries.

HEART is a simple, flexible, and effective method for determining the human error involved in accidents. Therefore, it has been used in various industries with complex systems, such as nuclear power plants, railway transportation, aviation, off-shore platforms, and the maritime industry (Akyuz et al. 2016; Bowo and Furusho 2019a; Castiglia et al. 2015; Deacon et al. 2013; Gibson et al. 2013; Wang et al. 2018b). There have been some developments of the HEART method to handle its limitations, especially for calculating the value of human error probability (HEP). The fault tree analysis and fuzzy set theory were hybridized with the HEART method to determine the HEP in irradiation plants (Casamirra et al. 2009; Castiglia and Giardina 2011). The fuzzy set theory was also employed to assess the HEP in hydrogen refueling stations (Castiglia and Giardina 2013). In the maritime industry, the HEART method has been integrated with the analytic hierarchy process (AHP) method to determine the specific value of an error producing condition (EPC) (Akyuz and Celik 2015). In the railway industry, a combination of the fuzzy analytic network process (FANP) and HEART method is utilized to determine the weight of the assessed proportion effect (APE) for HEP calculation (Wang et al. 2018b). The fuzzy logic theory has been combined with the HEART method to solve the linguistic expressions of expert elicitations to determine the appropriate weight to an EPC ( Kumaret al., 2017).

In light of the above explanation, many developments of the HEART method have been realized in various industries. Although several developments of the HEART method have overcome its limitations and shortcomings, most of these developments lack consideration of the relation between EPCs. In the maritime working environment, machinery, environment, and management can also influence the human condition to make judgments and control the situation. Furthermore, these factors have a strong relationship with human factors. This condition has been described in the HEART – 4M method, where the EPCs are categorized into four factors: man, machine, media, and management. However, the relationship between the factors and the HEP calculation process is still an issue. To remedy this gap, this study proposes a HEART – 4M method by combining it with the technique for order preference by similarity to ideal solution (TOPSIS) to evaluate the HEP in maritime accidents. The TOPSIS is introduced to handle the determination of the APE and the relation between factors. This paper presents a modified HEART – 4M method combined with TOPSIS to assess human error probability for collision accidents in Indonesia.

## 2 METHODOLOGY

This study proposes a modified method to evaluate HEP by incorporating the HEART method, 4M framework, and TOPSIS method in maritime collision accidents. Therefore, a description of these methods is provided below.

### 2.1 *HEART method*

HEART, established by Williams (1988), is a robust method to evaluate the HEP with defined error probability values. There are two fundamental parameters described in the HEART method: the generic task (GT) and the EPC. The GT parameter consists of nine qualitative descriptions of the appropriate task in the accident process, which is carried out by the assessor when analyzing the case. The GT also provides values of generic error probability, named nominal human unreliability (NHU), for every GT. The second fundamental parameter is the EPC, which indicates the relevant performance shaping factors for humans during the course of a task and can affect the value of HEP. The EPC can be any internal human feature or be related to other factors such as machine, management, and environment. There are 38 EPCs defined in the HEART method, and every EPC is provided with a multiplied number, which will later be used to calculate the HEP.

In light of the above, the calculation formula to determine the value of EPC is shown below:

$$HEP_{value} = NHU \times \left\{ \prod_i \left( EPC_i - 1 \right) APE_i + 1 \right\} \tag{1}$$

Table 1. Generic Tasks (GT).

| Generic Tasks (GT) Code | Type of work | Condition | NHU |
|---|---|---|---|
| A | Totally unfamiliar | Performing the work at speed with no real idea of likely consequences. | 0.55 |
| B | Restore the system to an original state on a single attempt | Doing work without supervision or procedures. | 0.26 |
| C | Complex task | It requires a high level of comprehension and skill. | 0.16 |
| D | A fairly simple task | Performing the work rapidly or given scant attention. | 0.09 |
| E | The routine, highly practiced, rapid task | Involving a relatively low level of skill. | 0.02 |
| F | Restore a system to original | An error occurred even though following procedures with some verification. | 0.003 |
| 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, totally aware of implications of failure, with time to correct the potential error | 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 | Miscellaneous task for which no description can be found. | | 0.03 |

where NHU is the error probability value of the relevant GT, and EPCi is the ith (i = 1,2,3, ⋯n) error producing condition, and the assessed proportion effect (APE) is a weight that corresponds to the importance of every EPC. As the EPC influence in the case becomes more critical, the value of the APE will be higher.

### 2.2 *HEART – 4M method*

The HEART – 4M method is a methodological extension of the conventional HEART method, which was introduced by Bowo and Furusho (Bowo and Furusho 2019b).

The HEART – 4M method is similar to the conventional HEART method, which consists of qualitative and quantitative approaches. In the qualitative approach, the selection of the relevant GT and NHU for the particular conditions before the accident uses the same GT parameter as the conventional HEART. Table 1 presents the GT and NHU used in this study.

However, in the HEART – 4M method, there is a categorization of the EPCs into the 4M framework, which consist of man, machine, media, and management. In the maritime working condition, the human condition can be influenced by machine, media, and management factors while performing tasks. Moreover, the 38 EPCs that were established by William describe the working condition, not only the error exclusively due to the human himself, but also to the interaction between humans, human–machine interactions, and working environment conditions. Table 2 presents the EPC – 4M categorization and the multiplication number. Therefore, with this categorization, the relationships between factors and the involvement of other factors in maritime accidents are now well addressed. Table 2 lists the categorization of the EPC and 4M factors and the multiplication of every EPC that will be used in the HEP calculation. There are five and four sub-factors in the man and management factors, respectively. Furthermore, the quantitative approach to calculate the result of HEP is based on Formula (1).

As mentioned above, the conventional HEART and HEART – 4M methods have limitations in describing the dependencies among EPCs and determining the weight of the APE to eliminate the uncertainties in error probability calculation. Therefore, TOPSIS is applied to modify the HEART – 4M method for developing an assessment to determine the weight value of the APE.

Table 2. EPC – 4M categorization and the multiplication

| Man Factors | | × |
|---|---|---|
| Physical limitations | | |
| EPC 27 | Physical capabilities | 1.4 |
| EPC 36 | Task pacing | 1.06 |
| EPC 38 | Age | 1.02 |
| Psychological limitations | | |
| EPC21 | Dangerous incentives | 2 |
| EPC28 | Low meaning | 1.4 |
| EPC 29 | Emotional stress | 1.3 |
| EPC 31 | Low morale | 1.2 |
| EPC 34 | Low mental workload | 1.1 |
| Experience | | |
| EPC 1 | Unfamiliarity | 17 |
| EPC 12 | Misperception of risk | 4 |
| EPC 22 | Lack of experience | 1.8 |
| Skill and Knowledge | | |
| EPC 7 | Irreversibility | 8 |
| EPC 9 | Technique unlearning | 6 |
| EPC 11 | Performance ambiguity | 5 |
| EPC 15 | Operator inexperience | 3 |
| EPC 20 | Educational mismatch | 2 |
| Health | | |
| EPC 30 | Ill-health | 1.2 |
| EPC 35 | Sleep cycles disruption | 1.1 |
| Machine Factors | | |
| EPC 3 | Low signal-noise ratio | 10 |
| EPC 8 | Channel overload | 6 |
| EPC 23 | Unreliable instruments | 1.6 |
| Media Factors | | |
| EPC 33 | Poor environment | 1.15 |
| Management Factors | | |

| | | |
|---|---|---|
| Communication | | |
| EPC 13 | Poor feedback | 4 |
| EPC 14 | Delayed/incomplete feedback | 3 |
| EPC 16 | Impoverished information | 3 |
| EPC 18 | Objectives conflict | 2.5 |
| EPC 19 | No diversity of information | 2.5 |
| Coordination | | |
| EPC 2 | Time shortage | 11 |
| EPC 6 | Model mismatch | 8 |
| EPC 10 | Knowledge transfer | 5.5 |
| EPC 24 | Absolute judgments required | 1.6 |
| EPC 25 | Unclear allocation of function | 1.6 |
| EPC 37 | Supernumeraries/ lack of human resources | 1.03 |
| Monitoring | | |
| EPC 17 | Inadequate Checking | 3 |
| EPC 26 | Progress tracking lack | 1.4 |
| Procedures | | |
| EPC 4 | Features over-ride allowed | 9 |
| EPC 5 | Spatial and functional incompatibility | 8 |
| EPC 32 | Inconsistency of displays | 1.2 |

## 2.3 *TOPSIS*

TOPSIS is a multi-criteria decision-making tool. TOPSIS was introduced in 1981 by Hwang and Yoon (1981), and it has been widely used in complex decision-making problems in various domains. TOPSIS aims to calculate the importance weight of alternatives through their similarity with an ideal solution (Krohling and Pacheco 2015; Olson 2004). TOPSIS comprises the set of processes described below. The first process constructs a pair-wise comparison matrix. The Saaty's 1–9 linguistic relative importance scale is used (Saaty 1985).

Table 3. Saaty's pair-wise comparison scale.

| Importance scale | Definition |
|---|---|
| 1 | Equal importance |
| 3 | Moderate importance |
| 5 | Strong importance |
| 7 | Extreme importance |
| 9 | Absolute extreme importance |
| 2, 4, 6, 8 | Intermediate values |

1 A pair-wise comparison matrix (D) can be established in accordance with Formula (2). In the formula, xij (i = 1, 2, …, m, j = 1, 2, …, n) has the relative importance of the ith element compared to the jth. In this study, every selected EPC will be compared to the other selected EPCs to determine the interdependencies of EPCs. By comparing these EPCs, it can be observed that every EPC is related to each other, and there will be a tendency for an EPC to be a major factor in an accident.

$$D=\begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \tag{2}$$

$$x_{ii}=1, \qquad x_{ij}=1/x_{ji},\ x_{ji}\neq 0$$

2 The normalized decision matrix is constructed and weighted.

Normalized decision matrix

To construct the normalized decision matrix, first, the attribute weight ($w_i$) for each EPCi must be obtained by utilizing Formula (3).

$$w_i=\sqrt{\sum_{i=1}^{m} x_{ij}^2} \tag{3}$$

After obtaining the attribute weight, the normalized decision matrix (r_ij) is constructed by dividing the value from the pair-wise comparison matrix to the attribute weight, as shown in Formula (4).

$$r_{ij}=\frac{x_{ij}}{w_i} \tag{4}$$

Weighted normalized decision matrix.

$$p_{ij}=r_{ij}\times x_{ij} \tag{5}$$

3 The ideal and negative ideal solutions are determined.

Ideal solution

$$d_{ij}^{+}=(p_{ij}-p_{i\,max})^2 \tag{6}$$

Negative ideal solution

$$d_{ij}^{-}=(p_{ij}-p_{i\,min})^2 \tag{7}$$

4 The separation from the ideal solution is determined.

$$d_i^{+}=\sqrt{\sum_{j=1}^{n}(d_{ij}^{+})^2} \tag{8}$$

5 The separation from the negative ideal solution is determined.

$$d_i^{-}=\sqrt{\sum_{j=1}^{n}(d_{ij}^{-})^2} \tag{9}$$

6 Relative closeness to the ideal solution.

$$\xi_i=\frac{d_i^{-}}{d_i^{+}+d_i^{-}} \tag{10}$$

7 Normalization.

The summation of all the EPC ideal solution values is not one, it is often more than one and sometimes even less than 1. Thus, it needs to be normalized before using this value for the HEP calculation. The last value used in the HEP calculation is the normalization value (N) to be the weight in the APE. This value shows which EPC has the highest value of weight, which implicates this is the main factor of the accident because its particular EPC is the most important compared with other EPCs. If the weight is approved, then it can be used for the HEP calculation. Therefore, in this study, the highest value of EPC was named the top of the EPC series. Formula (11) shows the calculation formula for the normalization value.

$$\mathrm{N} = \frac{\xi_i}{\sum} \tag{11}$$

8 Consistency verification

The next step proves the consistency of data. This step verifies whether the comparison pair-wise matrix is consistent or not. The consistency index (CI) can be calculated using the following formula:

$$\sum_{j=1}^{n} x_{ij} N = \lambda_{max} N_i \tag{12}$$

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{13}$$

A consistency verification calculation is needed to specify a reasonable consistency. The consistency ratio (CR) value was $\leqslant$ 0.10. Otherwise, the expert judges will be revised to obtain consistent results.

$$CR = \frac{CI}{RI} \tag{14}$$

In the equation, RI stands for random index. It is subjected to a number of items that are compared in the matrix. The RI values are provided in Table 4.

Table 4. Random index values (Saaty 1994).

| n | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| RI | 0 | 0 | 0.58 | 0.90 | 1.12 |
| n | 6 | 7 | 8 | 9 | 10 |
| RI | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 |

## 3 RESULTS

In this study, data on maritime collision accidents from the Indonesian National Transportation and Safety Committee in the period of 2009–2018 were used. In total, 13 data sets were collected, and 23 ships were involved in the analysis. The types of ships involved in collision accidents were container ships, bulk carriers, tanker ships, cargo ships, passenger ships, and tug boats. The cases that have been analyzed are ships with more than 500 GT.

### 3.1 *Generic Task*

From the 23 ships involved in collision accidents in Indonesia, Table 5 presents the tabulation of the selected GT. The most common situations encountered by Indonesian ships are routine, highly practiced, and rapid tasks that involve a relatively low level of skill. This shows that there are 17 ships that had the same working situation before the accidents occurred.

All of the collision accidents occurred when the ship sailed in or out to the destination port, which has a high density and congested traffic. Nineteen cases started as a fairly simple task, under the condition where the navigation team received help from the tug boat or pilot to enter or exit the port. The condition considers that the pilot and tug boat pilots are already familiar with the water's situation. It is included in the category of a fairly simple task, but it was performed rapidly and received scant attention. In addition, there were four ships that entered and exited the port without the tug boat or local pilot assistance, although there are rules that govern this. This type of situation requires a high level of skill and is included in the complex task type because assistance is required to carry out this job properly.

Table 5. Generic task result

| Code | Type of work | Total |
|---|---|---|
| D | A fairly simple task | 19 |
| C | Complex task | 4 |

### 3.2 *EPC – 4M*

There are 101 selected EPCs for the 23 ships that have been assessed. The total of EPCs in the man factor is 47, which are divided into four sub-factors: physical, psychological, experience, and skill and knowledge. Misperception of risk is the most common EPC found in Indonesian cases. Moreover, the educational mismatch was also found, and four cases were identified. In these cases, the seafarer did not have qualified education to work onboard. However, due to the shortage of crew, unqualified seafarers were employed.

Management factors have more EPCs than the man factors. There were 54 EPCs found, consist of communication, coordination, and monitoring sub-factors that affect collision accidents in Indonesia. The most common EPCs found belong to monitoring sub-factors in management factors. They correspond to EPC 17, inadequate verification for 14 ships, and EPC 26, lack of progress tracking for 12 ships.

Moreover, five ships had machine factors due to unreliable instruments. Only one case has media factors. The details of EPCs found in Indonesia collision accident cases are summarized in Table 6.

Table 6. EPC – 4M results

| Man Factors | | |
|---|---|---|
| Physical | | |
| EPC 36 | Task pacing | 2 |
| Psychological | | |
| EPC 21 | Dangerous incentives | 4 |
| EPC 28 | Low meaning | 2 |
| EPC 29 | Emotional stress | 2 |
| EPC 34 | Low mental workload | 4 |
| Experience | | |
| EPC 1 | Unfamiliarity | 1 |
| EPC 12 | Misperception of risk | 9 |
| EPC 22 | Lack of experience | 6 |
| Skill and Knowledge | | |
| EPC 20 | Educational mismatch | 4 |
| EPC 9 | Technique unlearning | 1 |
| EPC 11 | Performance ambiguity | 6 |
| Machine Factors | | |
| EPC 23 | Unreliable instruments | 5 |
| Management Factors | | |
| Communication | | |
| EPC 10 | Knowledge transfer | 4 |
| EPC 13 | Poor feedback | 9 |
| EPC 16 | Impoverished information | 3 |
| EPC 18 | Objectives conflict | 2 |
| EPC 19 | No diversity of information | 1 |
| Coordination | | |
| EPC 2 | Time shortage | 4 |
| EPC 24 | Absolute judgments required | 1 |
| EPC 37 | Supernumeraries/lack of human resources | 4 |
| Monitoring | | |
| EPC 17 | Inadequate verification | 14 |
| EPC 26 | Lack of progress tracking | 12 |
| Media Factors | | |
| EPC 33 | Poor environment | 1 |
| Total 101 | | |

### 3.3 *HEP Calculation*

In this section, we consider one of the cases to be the calculation example of this proposed method. The following calculation description is from case number one, with the following details: this accident occurred on May 22nd, 2009, at 17:28 in Madura Strait, Surabaya. The weather conditions at that time were fine, with calm winds and currents of 1.8 knots from the west. This accident involved two ships, a container ship of 5,283 GT and a general cargo ship of 8,639 GT. However, the accident report on NTSC only stated the container ship condition. Therefore, the analysis of case number one only assessed one ship.

In case one, there are five EPCs selected, which comprised EPC 11, EPC 21, EPC 12, EPC 29, and EPC 1. To determine the APE weight of each of these EPCs, the data are processed using TOPSIS, as follows:

1 Pair-wise comparison matrix (D)

After selecting the EPCs that caused the accident in the accident report, the next step in calculating the APE weight value is constructing the pair-wise comparison matrix, as presented in Table 7. In the matrix, every EPC is selected by putting the importance scale and using Formula (2) to calculate the proportion.

The attribute weight ($w_i$) in this table is calculated using Formula (3). The attribute weight value is used in the next step to construct the normalized decision matrix.

Table 7. Pair-wise comparison matrix and attribute weights ($w_i$)

| | EPC11 | EPC21 | EPC12 | EPC29 | EPC1 | $w_i$ |
|---|---|---|---|---|---|---|
| EPC11 | 1 | 0.33 | 3 | 3 | 0.5 | 4.40 |
| EPC21 | 3 | 1 | 0.2 | 0.33 | 0.25 | 3.20 |
| EPC12 | 0.33 | 5 | 1 | 0.2 | 0.33 | 5.12 |
| EPC29 | 0.33 | 3 | 5 | 1 | 0.25 | 5.93 |
| EPC1 | 2 | 4 | 3 | 4 | 1 | 6.78 |

2 The normalized decision matrix is constructed and weighted.

Normalized decision matrix

After calculating the attribute weight ($w_i$), then the normalized decision matrix is constructed, Table 8, by utilizing Formula (4).

Table 8. Normalized decision matrix

| | EPC11 | EPC21 | EPC12 | EPC29 | EPC1 |
|---|---|---|---|---|---|
| EPC11 | 0.23 | 0.08 | 0.68 | 0.68 | 0.11 |
| EPC21 | 0.94 | 0.31 | 0.06 | 0.10 | 0.08 |
| EPC12 | 0.07 | 0.98 | 0.20 | 0.04 | 0.07 |
| EPC29 | 0.06 | 0.51 | 0.84 | 0.17 | 0.04 |
| EPC1 | 0.29 | 0.59 | 0.44 | 0.59 | 0.15 |

Weighted normalized decision matrix.

In the weighted normalized decision matrix, in Table 9, the maximum weight ($p_{(i\ max)}$) and the minimum weight ($p_{(i\ min)}$) for every EPC, listed in Table 10, are used. The maximum weight is used to calculate the ideal solution matrix, and the minimum weight will be used for the negative-ideal solution matrix.

Table 9. Weighted normalized decision matrix

| | EPC11 | EPC21 | EPC12 | EPC29 | EPC1 |
|---|---|---|---|---|---|
| EPC11 | 0.23 | 0.03 | 2.05 | 2.05 | 0.06 |
| EPC21 | 2.82 | 0.31 | 0.01 | 0.03 | 0.02 |
| EPC12 | 0.02 | 4.88 | 0.20 | 0.01 | 0.02 |
| EPC29 | 0.02 | 1.52 | 4.22 | 0.17 | 0.01 |
| EPC1 | 0.59 | 2.36 | 1.33 | 2.36 | 0.15 |

Table 10. Maximum and minimum weight

| MAX | MIN |
|---|---|
| 2.05 | 0.03 |
| 2.82 | 0.01 |
| 4.88 | 0.01 |
| 4.22 | 0.01 |
| 2.36 | 0.59 |

3 The ideal and negative ideal solutions are determined.

Ideal solution matrix and separation from the ideal solution $d_i^+$

The ideal solution is the maximum limit that can be reached for every EPC from the calculation, as presented in Table 11.

Table 11. Ideal solution matrix and separation from the ideal solution $d_i^+$.

| | EPC11 | EPC21 | EPC12 | EPC29 | EPC1 |
|---|---|---|---|---|---|
| EPC11 | 3.31 | 4.08 | 0 | 0 | 3.95 |
| EPC21 | 0.00 | 6.27 | 7.86 | 7.74 | 7.82 |
| EPC12 | 23.59 | 0.00 | 21.93 | 23.72 | 23.59 |
| EPC29 | 17.61 | 7.28 | 0.00 | 16.38 | 17.68 |
| EPC1 | 3.13 | 0 | 1.06 | 0 | 4.89 |
| $d_i^+$ | 23.82 | 8.81 | 15.43 | 23.92 | 28.97 |

Negative ideal solution matrix and separation from negative ideal solution $d_i^-$.

The negative ideal solution is the minimum value that can be reached for every EPC from the calculation, as presented in Table 12.

Table 12. Negative ideal solution matrix and separation from the negative ideal solution $d_i^-$.

| | EPC11 | EPC21 | EPC12 | EPC29 | EPC1 |
|---|---|---|---|---|---|
| EPC11 | 0.04 | 0 | 4.08 | 4.08 | 0.0009 |
| EPC21 | 7.86 | 0.09 | 0.00 | 0.00 | 0.00 |
| EPC12 | 0.00 | 23.72 | 0.04 | 0.00 | 0.00 |
| EPC29 | 0.00 | 2.27 | 17.68 | 0.02 | 0.00 |
| EPC1 | 0.00 | 3.13 | 0.54 | 3.13 | 0.20 |
| d_i^- | 3.95 | 14.61 | 11.17 | 3.62 | 0.10 |

4 Relative closeness to the ideal solution and normalization

After obtaining the result of the ideal and negative ideal solution, the relative closeness to the ideal solution must be calculated using Formula (10). Because the summation of all the values of relative closeness to the ideal solution is more than 1 in this example, it needs to be normalized to the total weight. Table 13 lists the values of relative closeness to the ideal solution and its normalization value.

Table 13. Relative closeness to ideal solution and normalization

| | EPC11 | EPC21 | EPC12 | EPC29 | EPC1 | Total |
|---|---|---|---|---|---|---|
| $\xi_i$ | 0.14 | 0.62 | 0.42 | 0.13 | 0.0034 | 1.32 |
| N | 0.11 | 0.47 | 0.32 | 0.10 | 0.0026 | 1.00 |

5 Consistency verification

Before using the normalization value in the HEP calculation, the consistency of the value given in the pair-wise comparison matrix needs to be verified. The CI can be calculated using Formula (12), as presented in Table 14. The RI value was established by Saaty because, in this case, the number of EPCs found was five, and the RI assigned for calculating the CR was 1.1086. If CR $\leqslant$ 0.1, the normalization can be accepted and used in the HEP calculation.

Table 14. Consistency check

| CI | RI | CR |
|---|---|---|
| 0.07 | 1.1086 | 0.061 |

6 HEP Calculation

Table 15 presents the calculation example of the HEP result for case number one. The GT that was selected for the condition before the accident is a complex task that requires a high level of comprehension and skill, which has an NHU of 0.16 because it enters the Madura strait without guidance from a local tug boat. Table 15 presents the EPC series in case one, which has EPC 21 as the top of EPC series, followed by EPC 12, EPC 11, EPC 29, and EPC 1.

Table 15. HEP Calculation

| TOP | | BODY | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| EPC 21 | | EPC 12 | | EPC 11 | | EPC 29 | | EPC 1 | |
| × | APE | × | APE | × | APE | × | APE | × | APE |
| 2 | 0.47 | 4 | 0.32 | 5 | 0.11 | 1.3 | 0.09 | 17 | 0.003 |
| HEP Value | 0.71 | | | | | | | | |

Figure 1 shows the results of the twenty-three ships that were assessed using the proposed methods, HEART – 4M and TOPSIS. The figure shows that one or two ships are assessed in one case. The value of HEP varied for each case. The average value of the Indonesian collision accident in Indonesia was 41%. The value of HEP can vary owing to the differences in the selected GT and the number of EPCs found in each case. If the selected GT has a higher NHU, the value of HEP can also be higher.

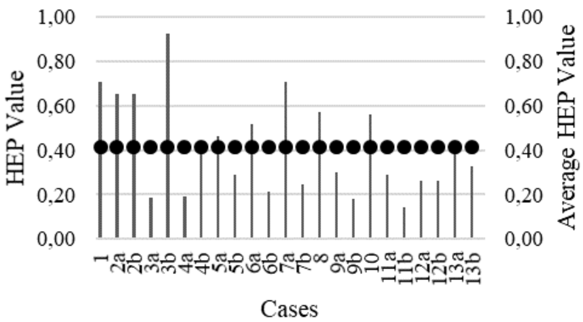


Figure 1. HEP Value of Indonesian collision accidents and average of the HEP value

4 DISCUSSION

Human factors are still the main factors of collision accidents in Indonesia. The analysis of the reviewed collision accidents in Indonesia shows that most accidents occurred during fairly simple tasks, which were rapidly performed and received scant attention. It means that the seafarers did not pay sufficient attention during their onboard work to manage satisfactory watchkeeping tasks. They thought they were familiar with the situation, and thus they tended to underestimate the task. Based on the EPC – 4M result, the management factors influenced the condition of humans during their work. The management factor becomes the most common EPC – 4M factor found in these cases, besides the man factor itself. This means that the tasks related to management and which require good teamwork, such as monitoring, communication, and coordination, must receive more attention. However, the EPCs belonging to man factors are also of concern, as it has been found that many of these factors influence the accidents. The Indonesian seafarer must be trained and educated well before working on board, and all the stakeholders of the Indonesian shipping companies have to obey the rules that have been issued by the authority for the safety at sea. In some cases, it was found that some seafarers did not have sufficient qualifications to work onboard, yet they worked, and did not have enough capacity to handle a certain condition to prevent accidents.

The HEART method is a robust tool for analyzing the human error probability. However, this method has some limitations to connect each EPC that has an attachment to other factors and to calculate the HEP value in the maritime industry. To overcome these limitations, first, the HEART method has been combined with the 4M factors to categorize the EPC into man, machine, media, and management factors (Bowo, Prilana, and Furusho 2019). This categorization can define all the 38 EPCs established by William in 1986 into the 4M factors, which are related to the maritime industry's working environment. This 4M factors are related to each other because each factor can also influence other factors. Second, TOPSIS is used to determine the weight of the APE for every selected EPC in the case by considering the relation of every EPC.

Finally, a hybrid method that integrates HEART – 4M and TOPSIS to calculate the maritime accidents in Indonesia was proposed. The integration of these methods suggests the relation between the EPC and the 4M method along with the dependencies among them. The problem with the relationships between factors and the involvement of other factors in maritime accidents is now well addressed. The TOPSIS method also helps the assessor to determine the weight of the APE for every selected EPC.

## 5 CONCLUSION

HRA is considered as a tool to determine the probability of human error and help the decision-maker to develop a mitigation process to avoid the same situation in the future. The purpose of this paper is to introduce a new method for quantifying the HEP in maritime accidents, in this case, collision accidents. Owing to some limitations of the HEART method, a number of developments of this method have been conducted. In this study, the HEART – 4M method, based on the TOPSIS method, is proposed to overcome the limitation of the HEART method for analyzing maritime accident cases. The TOPSIS method can be used to obtain the uncertainty of weight for every EPC and determine the dependencies among EPCs to determine the most influential EPC in a particular maritime accident. Furthermore, the result of the analysis of Indonesian maritime collision accidents shows that the most common GT is a fairly simple task that is rapidly performed and receives scant attention. Further, the EPCs of management factors are the most common causal factors found in these accidents. In conclusion, the hybrid method proposed in this study provides a practical tool to determine the value of HEP in maritime accidents.

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