

Delphi-AHP Based Methodology for Selecting Causal Factors of Marine Transportation Accidents

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Abstract

The causal factors of marine transportation accident are important to be identified in order to minimize the number of accidents that are reported over the years. The objective of this study is to establish the priorities (importance) of causal factors in causing accidents involving marine transportation that handles hazardous materials (HAZMAT). Two methods were employed, which are the Delphi and the Analytical Hierarchy Process (AHP) methods. As part of these methods, ten professionals in marine safety in Malaysia, both from the industries and academia, were selected to weigh their expert judgments on the prioritization of the causal factors based on the safety aspect of the HAZMAT marine transportation operation. From the study, 26 factors were pre-determined as a result of the Delphi method application, which was then further categorized into three main aspects of environment, technical and management. Weightings of each aspect were calculated using the AHP method through Expert Choice 2000 software to determine the pair-wise comparison between evaluated aspects contributing to marine transportation accidents. The integrated Delphi-AHP method as proposed in this study was suitable for retrieving a more efficient decision-making process among the top management in planning a comprehensive safety assessment for maritime shipping industries.

1. Introduction

Over the centuries up until the dawn of the modern era, the maritime transportation industry has been continuously linked with a vigorous number of marine transportation accidents. Marine incident has been defined as an event, or sequence of events, other than a marine casualty, which has occurred directly in connection with the operations of a ship that endangered, or, if not corrected, would endanger the safety of the ship, its occupants or any other person or the environment [1]. According to European Maritime Safety Agency (EMSA), marine casualties and incidents can be compared between different types of ship by using methodology to determine EU ship occurrence indicator. Statistic shows the higher average ship occurrence indicators in the period from 2013 to 2023 involved both passenger ships and cargo ships, 250 and 147 respectively [1]. Lloyd's Register-Fairplay World Casualty Statistics (2015) shows that various types of marine transportation accidents were reported, such as collision, contact and grounding [2],[3]. These accidents predominantly occurred along the sea voyage, particularly in the restricted area such as the port area [4]. Statistic from 2013 to 2023 recorded by EMSA also

shows that half of the reported marine casualties and incidents occurred in internal waters (port area and other) [1].

Such accidents, directly involved with a bulk amount of hazardous materials (HAZMAT) transported, often resulted in catastrophic impacts on the economy, human lives and also the environment. HAZMAT has become an essential material for the economic development and productivity of life [5],[6]. HAZMAT has defined as type of material with the potential of harm to people, the environment, and properties that consist of explosive, combustible, oxidizing, toxic, radioactive, infected, or acidic substances and hazardous wastes [7]. HAZMAT transportation may involve intra- or inter-cities and countries [7]. HAZMAT can be transported via few established transportation modes including road, railway, airway, and maritime [7],[8]. Main types of HAZMAT that being transported using maritime transportation is oil products which divide into two categories: (1) crude oil and (2) refined and processed petroleum products such as gasoline, Orimulsion, liquid natural gas, distillate, etc. [9]. Inadequate control in transporting the HAZMAT shipments may lead to incidents especially during loading, unloading or shipping process.

Basically, the accident risk in marine transportation has been monitored by the International Maritime Organization (IMO). In this context, IMO directly deals with maritime safety, maritime environment, maritime security and other legal matters [10]. Marine transportation accidents normally being reported through public and private institutions [11],[12]. At international level, IMO provides a database known as Global Integrated Shipping Information System (GISIS) with a dedicated portal to marine casualties and incidents [11]. With this insight, all issues related to maritime safety, especially accident risk evaluation, are a top priority to control despite the existence of various challenges. Furthermore, investigation on marine transportation accidents becoming one of the most cited topics in the literature review related to maritime transportation [11]. Risk defines as magnitude of potential losses and the likelihood of these losses, consequential from the uncertainty caused by the interface of multiple factors under certain conditions and within a specific period [13],[14].

To cater for this issue in detail, the structured Formal Safety Assessment (FSA) has been introduced [15]. Designed as a tool to assist maritime regulators, FSA method has been introduced to IMO in 1993 by United Kingdom as a risk management framework in the marine transportation [16]. Since then, FSA has become a main agenda of the Maritime Safety Committee of the IMO and it has been implemented as a rational risk-based methodology for regulatory purposes in marine industry. Although FSA is a well-known method to describe marine transportation risk in the current practices applied in the industries, there still exists a gap which needs to be filled up thoroughly. According to the previous study done by [17], it stated that FSA is unable to sort out all aspects of risk in the marine transportation domain simultaneously. Several challenges discovered during data collection and interpretation of the risk for example data may not been recorded in a format that can facilitate FSA. Therefore, it is notable concern on the incomplete information when FSA being applied to identify appropriate risk control measures that can reduce the occurrence of likelihood or mitigate the consequences [16]. In addition to that, FSA method involves extensive time and manpower [18],[19]. In other words, failing to attribute all causes of an accident could reflect unfavourably on the method performance and the outcomes that will be achieved.

Therefore, the purpose of this paper is to propose a new approach which is known as the Delphi-analytic hierarchy process (AHP) method for establishing the priorities (importance) of causal factors in causing accidents in marine transportation that handles HAZMAT. Delphi method involves input collection from experts panel through multiple rounds of anonymous questionnaires to achieve the objective of the study [20]. The original Delphi method uses an open-ended format for the first-round questionnaire while modified Delphi method using structured questionnaire [20],[21]. Delphi method has been used widely in research and its involved anonymous approach which allows participants to freely provide their judgements and responses. Furthermore, Delphi method shows results with high reliability through repeated questionnaire to gather input from the expert [22]. The AHP methodology is a multi-criteria decision-making method which provide an overall performance indicator through pairwise comparisons [22]. The AHP methodology will be used to prioritize the indicators and structures the decision-making process into hierarchy. It has been used to solve complex decision-making problems. Furthermore, AHP method can help to reduce bias and minimize consensus differences in experts panel [22],[23]. This has brought about an additional dimension to enhance the quality of safety assessment in marine transportation. The advantage of the Delphi-AHP method is its simplicity and it also does not require a large-scale data collection.

Identifying existing marine transportation accident sources and levels of HAZMAT transport complexity has thus become a crucial issue in order to conduct a comprehensive risk assessment. Furthermore, the marine transportation system itself is very complicated and the existence of many contributing factors including human factors, vessel specifications, route characteristics, atmospheric factors or weather conditions that lead to marine transportation accidents occurrence [24] also simultaneously become a huge challenge for the researchers. In order to do so, a detailed methodology to assess all these factors is expressed in Section 3, followed by results and a discussion on the priorities of marine transportation aspects in Section 4 and a conclusion in the final section.

2. Methodology

In this study, the methodology consists of gathering data associated with annual domestic and international accident reports of marine transportation, questionnaire surveys for the Delphi-AHP method, and a review of available literature. Technically, the proposed method (Delphi-AHP) is used to determine the weightage of three identified marine aspects, which are technical, management and environment. A flow diagram of the Delphi-AHP method has been illustrated in Fig. 1.

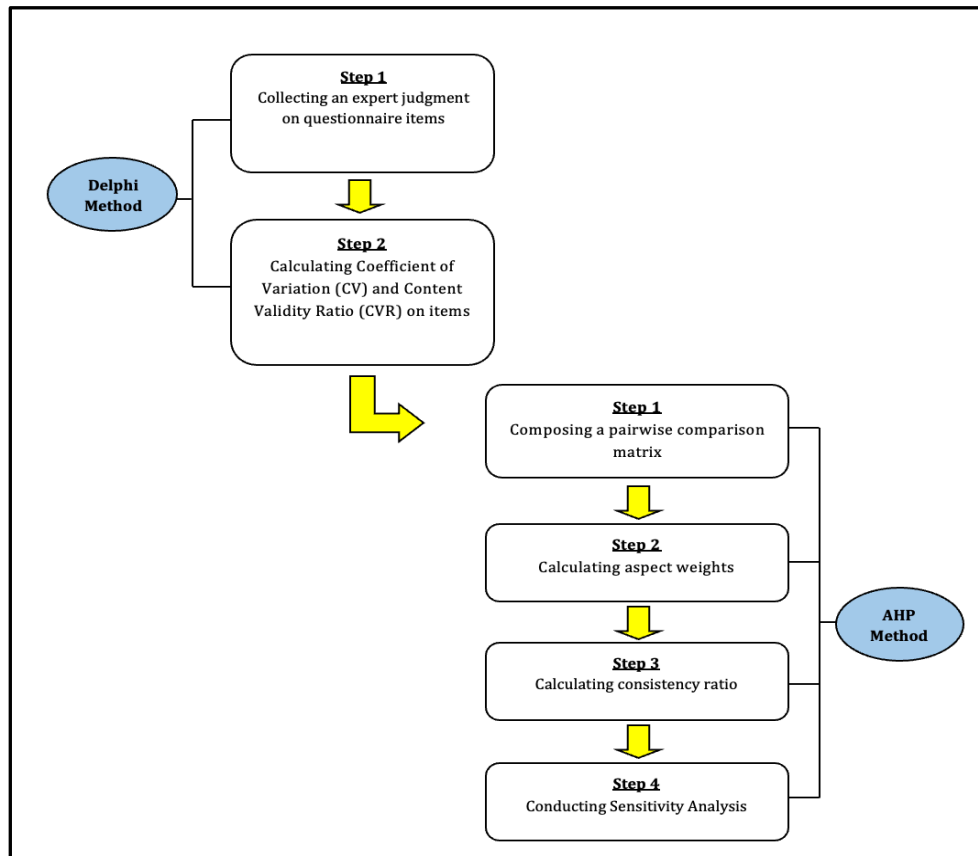


Fig. 1 Flow diagram of Delphi-AHP method

Initially, a review of available literature was carried out to place 26 causal factors in accordance with three main aspects (Fig. 2). Based on these identified aspects in previous study [25], a set of questionnaires was constructed, and followed by an online survey conducted among the 10 selected experts: 5 representatives from academia in Malaysian universities who are specifically involved in marine transportation area and 5 representatives from Malaysian marine industrial practitioners. Selection of the experts panel is critical, and it should be based on proficiency and up-to-date knowledge and also extensive experience in relevant field [22]. In this study, these experts were selected based on the working experience and knowledge on the operations and activities of marine transportation, as well as substantial familiarity with the current problems or issues took place in shipping industries. Every expert was asked to express a judgment on the tendency of every single aspect towards the occurrence of marine transportation accidents. These expert judgments were repeatedly analyzed using the Delphi method to achieve a comprehensive consensus on selecting the appropriate valuation criteria for each aspect. In addition to establishing the proposed method, the AHP method is simultaneously applied in order to reduce the difficulty in selecting the priority or weightage of each aspect in the decision-making process. Due to that, the AHP method could assess thoroughly the priorities of multiple alternatives which appeared from various valuation criteria by using a pair-wise comparison matrix. In order to study the priorities of marine transportation aspects, each aspect with the respective response from the experts was analyzed. A brief explanation of each step involved in this method is described in the following sub-section.

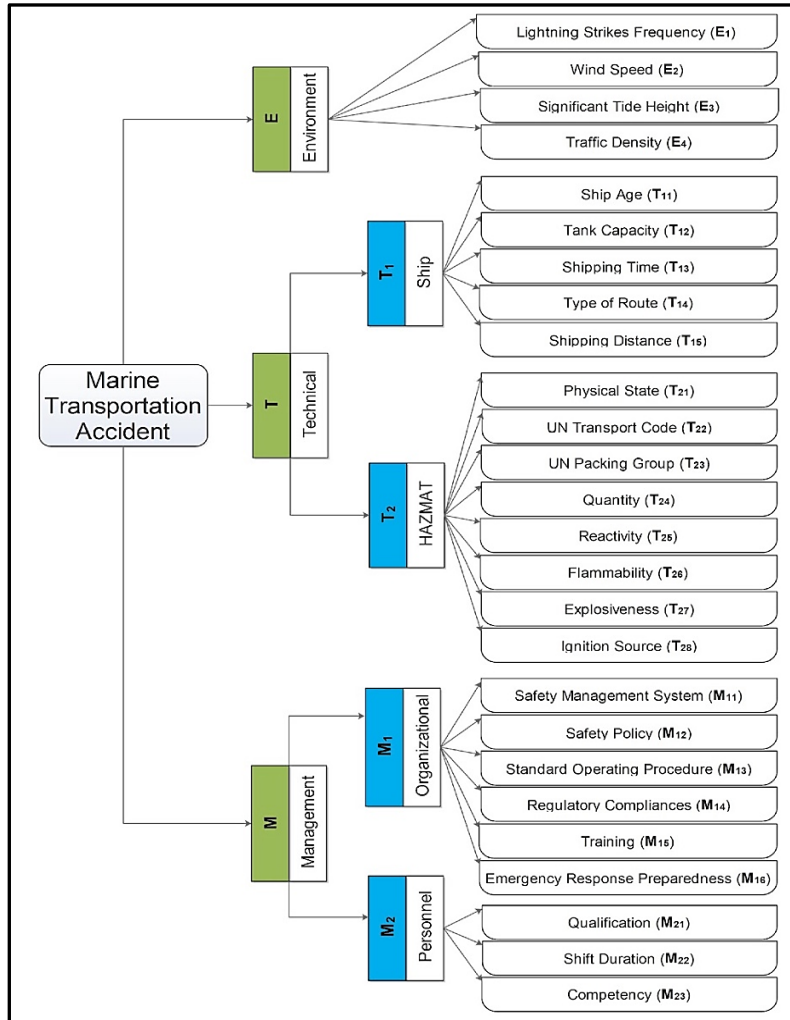


Fig. 2 Causal factors of marine transportation accidents

2.1 Calculation of Content Validity Using the Delphi Method

In the first step of the analysis, the chosen Delphi method is applied to rate how problematic or good each of the items available in the questionnaire. To illustrate this calculation, Equation 1 is established as follows:

$$CVR = \frac{ne - (\frac{N}{2})}{(\frac{N}{2})} \tag{1}$$

where ne = the number of experts indicating that a factor or parameter is essential and N = the total number of experts

2.2 Determination of the Aspects Weightage

Step 1: Evaluating the Input Using the AHP Pair-wise comparison matrix

In this step, the number of n x n pair-wise comparison matrix needs first to be determined prior to proceeding to the next steps. These pair-wise comparisons are made based on the relative measurement scales developed by [26] as shown in Table 1. Other values of 2, 4, 6 and 8, which are not presented in Table 1, are known as intermediate values. These values were used to represent shades of judgment between those five basic comparison scales with respect to the decision maker's perception of the aspect dominance.

Table 1 AHP pair-wise comparison scale

How important is A relative to B?	Comparison Scale
Equally importance	1
Weakly more importance	3
Strongly more importance	5
Very strongly importance	7
Absolutely more importance	9

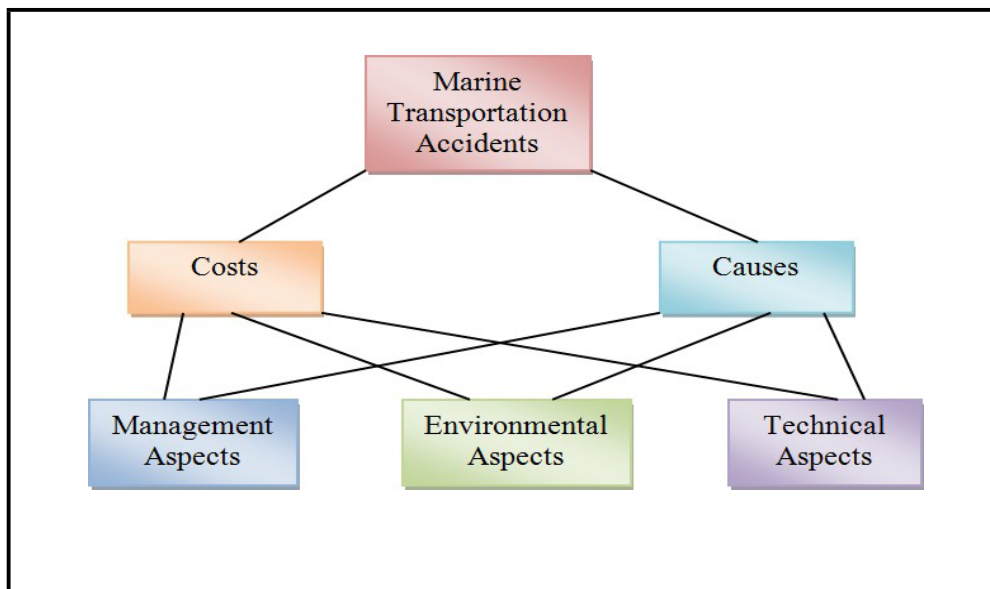
The aim was to establish the relative importance between the paired aspects in order to determine the respective weightage. By using the equation below (Equation 2), the number of $n \times n$ pair-wise comparison matrix can be determined:

$$\text{Number of comparisons} = \frac{n(n-1)}{2} \quad (2)$$

where n indicates the number of aspects being compared

In this step, the number of pair-wise comparisons between the aspects was calculated as 3; that means a 3×3 matrix is needed to be constructed for the following paired comparison (Fig. 3) to correspond to the 'costs' and 'causes' criteria as shown below:

- Environmental aspects (**E**) compared to technical aspects (**T**)
- Environmental aspects (**E**) compared to management aspects (**M**)
- Technical aspects (**T**) compared to management aspects (**M**)

**Fig. 3** The relative importance of each aspect

Step 2: Calculating the Weightage for Each Aspect

Next, the priority weightage vector, known as the eigenvector, W , is calculated for each aspect included in this study. The calculation is initially made by summing up all the values of collected input with regard to the respective column. Then, each input value is divided by the total sum of these values accordingly.

Step 3: Calculating Consistency Index

For calculating the Consistency Index (CI), the value of λ_{\max} needs to first be calculated. The CI represents a deviation or degree of consistency of the paired aspect. Meanwhile, the λ_{\max} is the largest eigenvalue of the matrix.

In order to calculate this value, each matrix cell is multiplied with the priority vector that has been calculated as follows:

$$CI = \frac{(\lambda_{max} - n)}{(n - 1)} \tag{3}$$

where CI, λ_{max} and n represent the consistency index, the largest eigenvalue and the size of the matrix respectively. According to [27], the $CI \leq 0.1$ is an acceptable range. Meanwhile, the randomized index (RI) values are shown in Table 2 [28]. This calculation can be presented with the following formula:

$$CR = \frac{CI}{RI} \tag{4}$$

Table 2 Random Consistency Index (RI)

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

When the CR value obtained from the calculation as shown above is smaller than or equal to 0.1 (≤ 0.1). This means all positive reciprocal matrices in the sample data are consistent. However, if the case is vice versa (> 0.1), the pair-wise comparison needs to be recalculated, or the questionnaire has to be revised.

Step 4: Sensitivity Analysis

The final step was conducting a sensitivity analysis. Sensitivity analysis has been performed by using Expert Choice 2000 software to investigate the effect of uncertainty of each aspect on the optimal solution.

3. Results and Discussion

After the evaluation of questionnaire items was conducted twice by the group of experts, 26 items (E1, E2, ..., M23) were finally warranted and therefore could be included in the finalized questionnaire. Specifically, the Coefficient of Variation (CV) and Content Validity Ratio (CVR) were calculated for each item of the questionnaire. The Coefficient of Variation (CV) was calculated based on the ratio of the standard deviation to the mean of responses from the experts. Meanwhile, Content Validity Ratio (CVR) is the measurement of consistency with regard to the number of responses given by the experts on how essential a particular item towards the research is conducted.

As presented in Table 3, the evaluation of each item satisfied the required levels of CV (< 0.5) and CVR (> 0.29). Based on [29], CV value less than 0.5 indicated no additional survey would be required for the study but if one of the CV values more than 0.5, the parameters may need to be modified, and additional survey is required. While for CVR, the minimum value of 0.29 is required for the inclusion of the parameter [30]. Therefore, all identified 26 items are relevant to the content domain of this research, which is related to assessing the parameters that potentially contribute to the occurrence of marine transportation accidents.

Table 3 CV and CVR results of questionnaire items

Items	Responses			Result			
	Not Necessary	Useful but not Essential	Essential	Mean	Standard Deviation	CV (<0.5)	CVR (>0.29)
E ₁	-	-	10	3.00	0.00	0.00	1.00
E ₂	2	1	7	2.50	0.85	0.34	0.40
E ₃	3	-	7	2.40	0.97	0.40	0.40
E ₄	-	2	8	2.80	0.42	0.15	0.60
T ₁₁	-	3	7	2.70	0.48	0.18	0.40
T ₁₂	2	-	8	2.60	0.84	0.32	0.60
T ₁₃	1	2	7	2.60	0.69	0.24	0.40
T ₁₄	-	1	9	2.90	0.32	0.11	0.80
T ₁₅	3	-	7	2.40	0.97	0.40	0.40
T ₂₁	-	1	9	2.90	0.32	0.11	0.80
T ₂₂	3	-	7	2.40	0.97	0.40	0.40
T ₂₃	3	-	7	2.40	0.97	0.40	0.40
T ₂₄	-	-	10	3.00	0.00	0.00	1.00
T ₂₅	1	2	7	2.60	0.69	0.24	0.40
T ₂₆	3	-	7	2.40	0.97	0.40	0.40
T ₂₇	3	-	7	2.40	0.97	0.40	0.40
T ₂₈	2	1	7	2.50	0.85	0.34	0.40
M ₁₁	-	-	10	3.00	0.00	0.00	1.00
M ₁₂	-	2	8	2.80	0.42	0.15	0.60
M ₁₃	-	-	10	3.00	0.00	0.00	1.00
M ₁₄	-	2	8	2.80	0.42	0.15	0.60
M ₁₅	-	-	10	3.00	0.00	0.00	1.00
M ₁₆	-	3	7	2.70	0.48	0.18	0.40
M ₂₁	1	2	7	2.60	0.69	0.24	0.40
M ₂₂	-	1	9	2.90	0.32	0.11	0.80
M ₂₃	2	1	7	2.50	0.85	0.34	0.40

3.1 Results of Cause Criteria

Table 4 and Table 5 show the preference results for the three aspects with regard to the cause criteria. Table 4 presents the results of pair-wise comparison obtained from all experts. The value with higher repetition number of feedback was selected to be addressed for example, based on the pair-wise comparison between the environmental and technical aspects, almost 4 experts gave the same score of 1/3. All the respective values were normalized by dividing each value with their total sum of value.

Table 4 Comparison of the aspect with respect to the cause criteria

Aspect	Experts									
	AC ₁	AC ₂	AC ₃	AC ₄	AC ₅	MP ₁	MP ₂	MP ₃	MP ₄	MP ₅
Environment compared to Technical	3	1/7	1/7	1/3	1/3	1/3	1	9	1/9	1/3
Management compared to Environment	3	7	5	3	1/3	5	1	1/9	9	5
Technical compared to Management	5	1/7	5	1/3	1/3	1/5	1/3	9	1/9	7

Table 5 shows the preference results for the three aspects with regards to the cause criteria. This is important to be identified in order to determine the contribution of these aspects regarding the cause criteria towards the occurrence of marine transportation accidents. Based on the result, the management aspects are the most preferred ones, followed by technical aspects and environmental aspects.

Table 5 *The normalized matrix with row average values for the cause criteria*

Cause Criteria	Environment	Management	Technical	Row Average
Environment	0.111	0.130	0.077	0.106
Management	0.556	0.652	0.692	0.633
Technical	0.333	0.217	0.231	0.261
TOTAL				1.000

Notes: $\lambda_{max} = 3.039$, $CI = 0.019$, $CR = 0.03 < 0.1$ (acceptable)

3.2 Results of Cost Criteria

Meanwhile, the results for the cost criteria are presented in Table 6 and Table 7. This criterion was calculated in similar steps that have been outlined in previous part which using Equation 3 and Equation 4. Then, the value stated in Table 6 with higher repetition number of feedback was selected to be address. Table 7 represent the result of the normalized matrix of the 'cost criteria'. Based on the result, management aspects became the most preferred ones for the cost criteria, followed by technical aspects and environment aspects.

Table 6 *Comparison of the aspect regarding the cost criteria*

Aspect	Experts									
	AC1	AC2	AC3	AC4	AC5	MP1	MP2	MP3	MP4	MP5
Environment compared to Technical	7	1/3	5	1/7	1/7	1/3	1	3	1/9	1/3
Management compared to Environment	7	7	7	7	1/5	7	1	1	9	1/5
Technical compared to Management	5	1/7	5	1/5	1/7	1/5	5	1/5	9	1/5

Table 7 *The normalized matrix with row average values for the cost criteria*

Cost Criteria	Environment	Management	Technical	Row Average
Environment	0.091	0.106	0.053	0.083
Management	0.636	0.745	0.789	0.724
Technical	0.273	0.149	0.158	0.193
TOTAL				1.000

Notes: $\lambda_{max} = 3.066$, $CI = 0.033$, $CR = 0.06 < 0.1$ (acceptable)

Then, the results from Table 5 and Table 7 were gathered and calculated in order to determine the final weightage for each aspect based on the two different criteria as mentioned above. Therefore, the final weightage achieved for all aspects were presented in Table 8.

Table 8 *The final weightage for each aspect*

Aspect	Weightage
Environment (W_E)	0.102
Management (W_M)	0.647
Technical (W_T)	0.251

As a result from the final weightage, it can be seen that the management aspects have the highest weightage, followed by technical aspects, and finally the environmental aspects. Due to that, the management aspects are identified as the main aspect that may contribute to the occurrence of marine transportation accidents. Moreover, the management aspects can also be regarded as quite acceptable with the increasing number of such accident if no proper action is implemented. The expert's responses obtained for each item should be emphasized during safety assessment in loading and unloading operation in maritime transportation by port authority. Study conducted by [31] has proposes a new framework to control maritime accidents inclusive of management actions, staff training, regulations and procedures. In addition to that, human errors have been identified as main factors that led to maritime accidents. Furthermore, statistics shows that human action during shipboard operation is the most significant contributing factor that led to marine casualties and incidents for the period from 2014 to 2023 [1]. Indirectly, the top management of shipping companies needs to review and re-allocate a huge budget in performing an adequate plan to maximize the safety of the HAZMAT transport operation without constraining business profit.

In order to define the weightage achieved for all identified aspects, it is better to check the consistency of the results based on sensitivity analysis. Fig. 4 illustrates the overall inconsistency of the matrix with respect to these three aspects by using Expert Choice 2000 software.

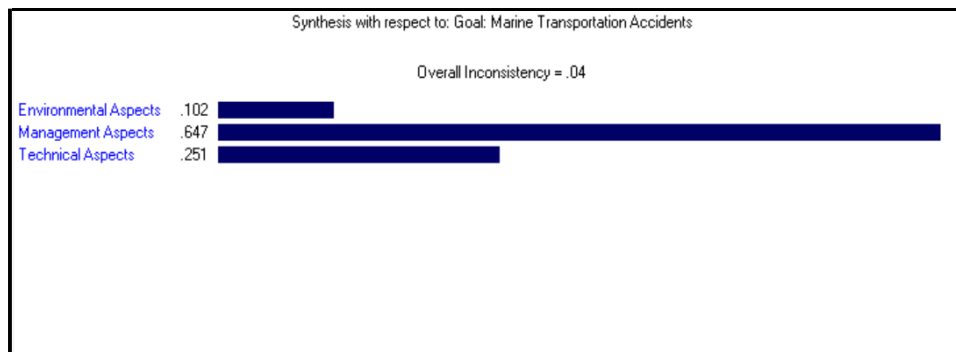


Fig. 4 Overall Inconsistency

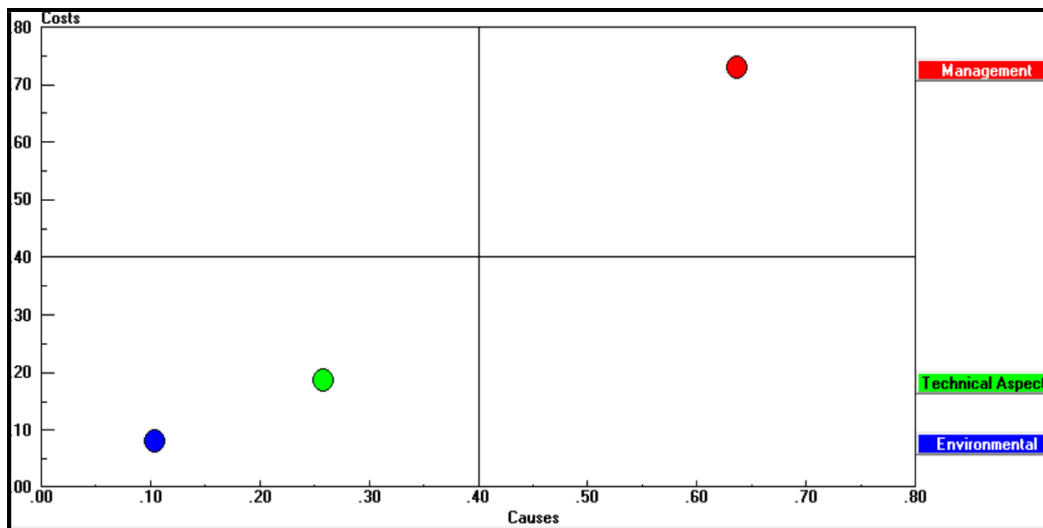


Fig. 5 Two-dimensional sensitivity graph

As a result, this clearly shows that a value of 0.1 or less (< 0.1) is acceptable and the degree of consistency of this matrix is not too high, which is 0.04. The most favourable aspect that is defined by the experts on the respective aspect will appear in the upper right quadrant (the closer to the upper right-hand corner, the better it is) as shown in Figure 5. In this study, the management aspects were identified and placed in that quadrant. On the other hand, the least favourable aspect was in the lower left quadrant, which is the environmental aspect. In other words, the environmental aspect has virtually less effect on the occurrences of marine transportation accidents since it is very close to the X-axis. Even though the environmental aspect is not directly a cause of the

accident, the combination of poor maintenance with other external conditions such as high traffic volume or bad weather may increase the chances for an accident to occur, without only focusing on the management aspects. The management aspects including the human element have a significant role in this category of accident. The most common problem is inadequate competency level and the seafarers lacking basic education about the requirements of their job.

4. Conclusion

This paper presents the decision-making on the priorities of aspects considered in the safety assessment of marine transportation of HAZMAT. The findings showed how the proposed Delphi-AHP method could derive the consensus of experts' responses to achieve the final decision among all causal factors and lastly determine the weighting of each aspect that contributed to the occurrence of marine transportation accidents. It is worth to highlight that the high value of management aspects is indicated as a highly possible cause of marine transportation accidents compared to a low-value aspect, which is environmental aspects. In other words, the overall result shows that the management aspect is defined as the most significant with the highest value of 0.647 while the environmental aspect is the least significant aspect with the lowest value of 0.102. Therefore, any changes and benefits with controlling management aspects in marine transportation activity can be addressed at the early stage of operation, and the improvements of these current practices are beneficial for enhancing marine transportation safety.

Since there were limited studies on marine accidents involving marine transportation of HAZMAT, this paper gives a user-friendly approach for marine safety practitioners and ship managers to be able in conducting accident investigations and analyzing all the causal factors thoroughly. By focusing on the right aspect, the top management can induce additional safety budget allocations, reduce non-competent crews recruited, improve technical skills through training capabilities, and elicit any malpractice during the HAZMAT transport operation. Finally, the Delphi-AHP method is suitable to be aided in the marine transportation risk assessment to make the elicitation easier and also to improve data quality prior to the involvement of experts' knowledge. While this method is quite practical to be applied in the maritime transportation industry, it can be applicable directly during the risk assessment of marine transport operations. Due to that, the number of similar accidents could be reduced from time to time.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

*The authors confirm contribution to the paper as follows: **study conception and design:** Mohd Najib Jacob, Mimi Haryani Hassim; **data collection:** Mohd Najib Jacob; **analysis and interpretation of results:** Mohd Najib Jacob; **draft manuscript preparation:** Mohd Najib Jacob. All authors reviewed the results and approved the final version of the manuscript.*

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