Analysis of Causes and Impacts of Tug and Barge Vessel Accidents Using the Analytic Hierarchy Process: A Case Study of XYZ Company

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***Abstract*—** Indonesia's maritime sector plays a strategic role in national logistics, where tug and barge vessels are widely used to transport bulk commodities due to their cost efficiency and operational flexibility. However, tug and barge operations face a high risk of accidents, particularly in densely trafficked waterways and challenging environmental conditions. This study aims to analyze the causes and impacts of tug and barge vessel accidents at Company XYZ during the period 2015–2024 and to determine priority mitigation measures using the Analytic Hierarchy Process (AHP). The study analyzes 170 recorded accident cases classified into human, technical, environmental, and procedural factors. The results show that human factors are the dominant cause, contributing 55.8% of accidents, followed by technical factors (26.3%), environmental factors (12.2%), and procedural factors (5.7%). The accidents resulted in material losses, operational delays of 3–7 days per incident, and environmental impacts such as fuel spills and onboard fires. The AHP results indicate that human-related factors are the highest priority for mitigation, followed by technical, environmental, and procedural factors, with a consistency ratio of 0.043, indicating acceptable reliability. This study provides a structured decision-making approach to support safety improvement and risk mitigation in tug and barge vessel operations.

Keywords—accident impact; decision making; human factor; maritime safety; risk prioritization; vessel operation

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I. INTRODUCTION

Indonesia is the world's largest archipelagic state, comprising more than 17,000 islands, making the maritime sector a strategic backbone of national connectivity and economic development. Maritime transportation dominates global trade, accounting for more than 80% of international cargo volume [1]. In Indonesia, tug and barge vessels play a crucial role in transporting bulk commodities such as coal, palm oil, and construction materials, particularly across Kalimantan, Sumatra, and eastern Indonesian waters. Their operational flexibility and relatively low cost make tug and barge systems a preferred mode for domestic logistics [2].

Despite these advantages, tug and barge operations are associated with a high risk of maritime accidents. Limited maneuverability, exposure to adverse weather conditions, congested waterways, and reliance on conventional navigation systems contribute significantly to accident occurrences. Several studies report that accidents involving tug and barge vessels in Indonesia frequently result in collisions, groundings, cargo losses, and environmental pollution [3]. In addition, the adoption of advanced maritime safety technologies such as Electronic Chart Display and Information System (ECDIS), Automatic Identification System (AIS), and real-time monitoring systems remains limited in this sector due to high investment costs, low digital literacy among crews, and the absence of mandatory regulatory enforcement for non-self-propelled cargo vessels [4].

Previous research on maritime accidents has largely emphasized the dominant role of human factors. The Swiss Cheese Model proposed by Reason explains that accidents occur when multiple layers of defense fail simultaneously, allowing human errors to penetrate system safeguards [5]. In the maritime fields, inadequate safety management, insufficient crew training, fatigue, and weak operational supervision have been identified as major contributors to accidents [6]. While these studies provide valuable insights, most existing research focuses on general shipping accidents or large commercial vessels, with limited empirical studies specifically addressing tug and barge operations based on long-term accident data at the company level.

Furthermore, prior studies often analyze accident causes descriptively without applying structured decision-making methods to prioritize mitigation strategies. This creates a research gap in developing a systematic and quantitative approach to rank accident causes and their impacts, particularly for tug and barge

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fleets operating in high-risk domestic waterways. Addressing this gap is essential to support evidence-based safety management and targeted risk mitigation in maritime operations.

Therefore, this study aims to analyze the causes and impacts of tug and barge vessel accidents at Company XYZ during the period 2015–2024 using the Analytic Hierarchy Process (AHP). The objectives of this research are to identify dominant accident factors, evaluate their operational, material, and environmental impacts, and determine priority mitigation measures based on structured decision analysis. The findings are expected to contribute to the development of practical safety strategies and enhance maritime risk management for tug and barge operations in Indonesia.

A. Previous Study

Numerous studies have examined maritime accidents with a primary focus on identifying dominant causal factors and improving navigational safety. Tug and barge operations are recognized as having distinct risk characteristics compared to conventional cargo vessels due to limited maneuverability, towing configuration complexity, and frequent operation in shallow or congested waterways. Wei Zhu et al. [7] highlight that tug and barge operations are particularly vulnerable to collisions and groundings in riverine and coastal environments with high traffic density.

Previous research consistently identifies human factors as the leading cause of maritime accidents. Chauvin et al. [8] emphasize that decision-making errors, fatigue, and reduced situational awareness play a significant role in accident occurrence. Similarly, Ishak [9] reports that the majority of maritime accidents are directly or indirectly linked to human error, especially communication failures and procedural violations. However, these studies predominantly focus on large commercial vessels or offshore operations and rely on aggregated accident databases, which limit their applicability to tug and barge fleets operating in domestic logistics routes.

Technical-related studies have also been widely conducted. Metin Celik [10] demonstrates that machinery failures, inadequate maintenance, and aging ship systems significantly contribute to loss-of-control accidents. While these studies provide valuable insights into technical reliability, they often analyze accident causes independently and do not integrate human, technical, and operational factors within a unified assessment framework.

Recent maritime safety research has introduced multi-criteria decision-making approaches to prioritize accident risks. Ahmet et al. [11] applied the Analytic Hierarchy Process (AHP) to rank ship operational risks based on expert judgment, proving its effectiveness in structuring complex safety problems. Nevertheless, most AHP-based studies focus on hypothetical scenarios or expert perception without incorporating long-term empirical accident data.

This study differs from previous research in several key aspects. First, it specifically focuses on tug and barge vessel operations, which remain underrepresented in maritime accident literature despite their critical role in domestic logistics. Second, the study utilizes ten years of actual accident data (2015–2024) from a single shipping company (Company XYZ), enabling a detailed and context-specific analysis of accident trends and impacts. Third, unlike prior studies that rely solely on descriptive statistics or expert judgment, this research integrates empirical accident data with the AHP method to quantitatively prioritize accident causes and mitigation strategies. By combining historical data analysis and structured decision-making, this study provides a practical and data-driven contribution to maritime safety management, particularly for tug and barge operations in developing maritime economies.

B. Factors of Tug and Barge Vessel Accidents

Tug and barge vessel accidents not only result in material and environmental losses but also pose serious threats to crew safety and maritime operational continuity. A comprehensive understanding of accident causation is therefore essential for effective risk mitigation. Based on maritime safety theory and previous literature, accident factors in tug and barge operations can be classified into human and technical factors.

1) Human Factors (Human Error)

Human factors are widely recognized as the dominant cause of maritime accidents. According to Reason's Swiss Cheese Model, accidents occur when multiple layers of defense fail, allowing human errors to penetrate system safeguards [12]. In tug and barge operations, human-related failures commonly include navigational errors, ineffective communication, crew fatigue, and inadequate training.

Navigational errors arise from incorrect chart interpretation, improper use of navigational aids, or poor route planning, which can lead to collisions and groundings [13]. Ineffective communication among crew members or with Vessel Traffic Services (VTS) further increases accident risk, particularly in congested waterways. Crew fatigue caused by excessive working hours and insufficient rest reduces alertness and cognitive performance, significantly impairing decision-making capabilities [14]. In addition, insufficient training and a lack of competency in emergency procedures increase vulnerability during abnormal operational conditions.

2) Technical Factors

Technical factors are associated with the condition and reliability of vessel machinery and equipment. International regulations such as SOLAS and the ISM Code require shipowners to ensure that vessels are seaworthy and properly maintained. However, failures in compliance often result in technical-related accidents.

Common technical failures include main engine or auxiliary engine breakdowns, which may lead to loss of propulsion or steering control during towing operations [15]. Steering gear malfunctions are particularly hazardous for tug and barge configurations, as they compromise directional stability in adverse weather conditions. Furthermore, malfunctioning navigational equipment such as radar, GPS, or echo sounders can lead to misjudgment of vessel position and surrounding traffic, increasing collision and grounding risks [16].

C. Analytic Hierarchy Process (AHP)

In maritime safety studies, AHP has been widely applied to prioritize accident causes, assess navigational risks, and support safety management decision-making [17]. By converting subjective expert judgments into numerical weights, AHP allows decision-makers to rank contributing factors based on their relative importance [18]. The consistency of judgments is evaluated using the Consistency Ratio (CR), where a CR value below 0.10 indicates acceptable reliability.

In this study, AHP is employed to prioritize tug and barge accident factors, including human, technical, environmental, and procedural aspects. The application of AHP enables a transparent and reproducible assessment framework, supporting evidence-based safety strategies and targeted risk mitigation in tug and barge vessel operations.

1) Definition of the Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making method developed by Thomas L. Saaty to address complex decision problems involving multiple and often conflicting criteria. AHP is designed to decompose a complex problem into a hierarchical structure, enabling systematic analysis and rational decision-making [19]. The hierarchy represents the problem in a multilevel structure, where the top level defines the main objective, followed by criteria, sub-criteria, and finally decision alternatives at the lowest level, as illustrated in **Figure 1**.

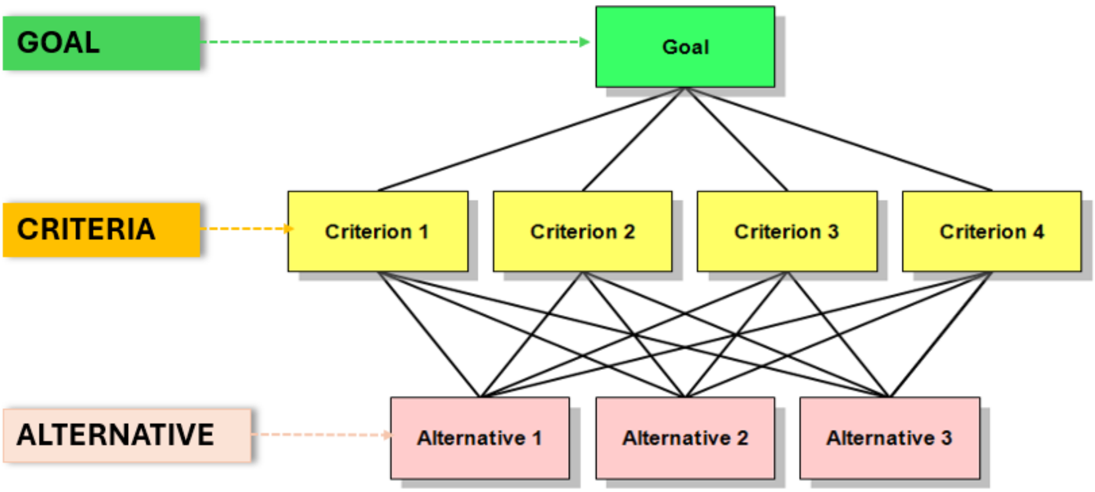
Through this hierarchical decomposition, complex decision problems can be divided into smaller, more manageable components that are logically structured and easier to evaluate. This approach allows decision-makers to assess both qualitative and quantitative factors in a consistent framework. AHP has been widely applied in engineering, management, and maritime safety studies due to its ability to incorporate expert judgment while maintaining analytical rigor [20].

The preference for AHP over other decision-making methods is attributed to several advantages. First, the hierarchical structure enables a clear breakdown of the decision problem from strategic objectives to operational criteria. Second, AHP provides a mechanism to evaluate the validity of judgments through consistency testing, ensuring that pairwise comparisons remain logically coherent. Third, AHP allows sensitivity analysis to examine the robustness of decision outcomes against changes in input judgments, enhancing the reliability of the results [21].

2) Stages of AHP Development

In general, the AHP methodology consists of three main stages: decomposition, comparative judgment, and synthesis of priorities, followed by an evaluation of logical consistency.

- Decomposition is the initial stage of AHP, where a clearly defined problem is broken down into smaller elements and structured into a hierarchy. The main objective is placed at the top level, followed by criteria and sub-criteria that influence the objective. This hierarchical structure may be complete, where all elements are fully interconnected, or incomplete, where certain elements do not have direct relationships. Decomposition facilitates a comprehensive understanding of the problem and ensures that all relevant factors are considered systematically [19].
- Comparative Judgment is conducted by comparing pairs of elements at the same hierarchical level relative to their influence on an element at the higher level. This process aims to determine the relative importance of each element through expert judgment. Pairwise comparisons are typically expressed using a numerical scale to reflect preference intensity and are organized into a pairwise comparison matrix. The results of this stage significantly influence the weighting of criteria and alternatives in the decision-making process [22].



. **Figure 1.** Analytic Hierarchy Process (AHP) Model

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- Synthesis of Priorities is performed after all pairwise comparison matrices have been established. Local priority weights are derived from each matrix by calculating eigenvectors, which represent the relative importance of each element. These local priorities are then aggregated across the hierarchy to obtain global priorities, enabling the identification of the most influential factors contributing to the decision objective. This synthesis process is critical for determining overall rankings and decision outcomes [23].
- Logical Consistency is a fundamental principle in AHP to ensure the reliability of judgments. Consistency refers to the logical coherence of pairwise comparisons. For example, if element A is judged more important than B, and B more important than C, then A should logically be more important than C. The level of consistency is measured using the Consistency Ratio (CR). A CR value below the accepted threshold indicates acceptable consistency, while values exceeding the threshold suggest that judgments should be reviewed and revised to improve reliability [19].

II. Method

This study employs the Analytic Hierarchy Process (AHP) as the primary analytical method. AHP is selected due to its capability to decompose complex decision-making problems into a structured hierarchical framework and to determine priority weights based on the relative importance of multiple criteria. The method is particularly effective for decision problems that involve both qualitative and quantitative considerations.

The application of the Analytic Hierarchy Process (AHP) follows a sequence of structured steps to ensure systematic and consistent decision-making. According to Suryadi and Ramdhani [24], the AHP procedure consists of the following stages:

1) Problem Definition and Identification of Alternatives

The first step in applying AHP is to clearly define the decision problem in a detailed and comprehensible manner for all stakeholders involved. A well-defined problem facilitates the formulation of appropriate analytical steps. Once the problem is identified, potential solutions or decision alternatives are determined. In many cases, a decision problem may involve multiple feasible alternatives, which are later evaluated and prioritized through pairwise comparison and priority analysis in subsequent stages.

2) Construction of the Hierarchical Structure

After defining the problem and decision objective, a hierarchical structure is developed as the foundation of the AHP analysis. The overall objective is placed at the top level of the hierarchy, followed by relevant criteria used to evaluate the alternatives. Each criterion represents a different evaluation aspect and may vary in importance. If necessary, criteria can be further decomposed into sub-criteria to provide a more detailed assessment. This hierarchical structure enables a clear representation of relationships among objectives, criteria, and alternatives.

3) Development of the Pairwise Comparison Matrix

At this stage, a pairwise comparison matrix is constructed to assess the relative importance of elements at the same hierarchical level. Each element is compared with every other element concerning its contribution to an element at the higher level. The comparisons are based on expert judgment and are organized in a matrix form, allowing systematic evaluation and consistency checking. This approach also enables sensitivity analysis to examine how changes in judgments influence priority results.

4) Definition of Pairwise Comparison Scale

In AHP, pairwise comparisons are performed using a numerical scale ranging from 1 to 9 to represent the relative importance between two elements. A value of 1 indicates equal importance, while values of 3, 5, 7, and 9 represent increasing levels of dominance, from moderate to extreme importance. Intermediate values (2, 4, 6, and 8) are used to express compromise judgments between adjacent scales. If element *i* is assigned a certain value relative to element *j*, then element *j* receives the reciprocal value when compared to element *i*. This scale, proposed by Saaty, has been widely validated in decision-making research [25]. The pairwise comparison scale is shown in **Table 1**.

TABLE 1.
PAIRWISE COMPARISON SCALE

Intensity of Importance	Verbal Definition	Explanation
1	Equal importance	Both elements contribute equally to the objective.
3	Slightly more important	Experience and judgment slightly favor one element over another.
5	Strong importance	Experience and judgment strongly favor one element over another.
7	Very strong importance	One element is clearly more important than the other; its dominance is evident in practice.
9	Extreme importance	Evidence indicates that one element is absolutely more important than the other.
2, 4, 6, 8	Intermediate values between two adjacent judgments	These values are used when a compromise between two judgments is required.

Note:
If element *i* is assigned one of the above values when compared with element *j*, then element *j* has the reciprocal value when compared with element *i*.

5) Eigenvalue Calculation and Consistency Test

Once the pairwise comparison matrix is completed, eigenvalues and eigenvectors are calculated to determine the relative priority weights of each element. These weights reflect the contribution of each criterion or alternative to the overall objective. To ensure logical coherence in the judgments, a consistency test is conducted. If the Consistency Ratio (CR) exceeds the acceptable threshold (generally 0.10), the comparison judgments must be revised to improve reliability and validity.

6) Repetition of Pairwise Comparison and Consistency Evaluation

Steps involving the construction of pairwise comparison matrices, eigenvalue calculation, and consistency testing are repeated for each level of the hierarchy. This iterative process ensures that all criteria, sub-criteria, and alternatives are evaluated comprehensively and consistently until final priority weights are obtained.

7) Eigenvector Computation

To determine priority weights, eigenvectors are calculated from each normalized pairwise comparison matrix. The normalization process involves dividing each element in a column by the sum of that column. Subsequently, the average value of each row is calculated to obtain the priority weight of each element. These eigenvectors represent the relative importance of elements and serve as the basis for determining global priorities within the hierarchy. The process of calculating the eigenvector is carried out by the following steps:

- Normalizing Each Column of Matrix A

The first step is to normalize each column of the pairwise comparison matrix A. This normalization is performed by dividing each element in column j by the sum of all elements in that column, resulting in the following equation:

$$A' = \sum a(i,j) = 1 \quad (1)$$

where $a(i,j)$ represents the elements of matrix A, and A' denotes the normalized matrix.

- Calculating the Average of Each Row

After the matrix has been normalized, the next step is to calculate the average value of each row i in matrix A'. This average is obtained by summing all values in row i and dividing the result by the total number of columns n. The formula used to compute the weight w_i for the i element is expressed as:

$$wi = \frac{1}{n} \sum a(i,j) \quad (2)$$

where w_i represents the relative weight of the i element, and n is the number of elements in the matrix. Through this process, a weight vector is obtained that reflects the relative importance of each element in the pairwise comparison matrix.

- Approximating the Solution of the Matrix Equation System

If matrix A is a pairwise comparison matrix, the corresponding weight vector can be approximated by solving the following matrix equation:

$$(A)(w^T) = (n)(w^T) \quad (3)$$

Using this approach, the relative weights of each element in the hierarchy are obtained and subsequently used to determine the global priorities in the decision-making process.

8) Consistency Evaluation of the Hierarchy

Consistency evaluation is a critical component of AHP to ensure the logical validity of judgments. The Consistency Index (CI) is calculated and compared with the Random Index (RI) to obtain the Consistency Ratio (CR). According to Salomon [26], a CR value of 0.10 or less indicates acceptable consistency. Although perfect consistency is difficult to achieve due to the subjective nature of human judgment, maintaining CR within the acceptable range ensures that the resulting priority weights are reliable and suitable for decision-making.

TABLE 2.
INCIDENT RECAPITULATION FROM 2015-2025

Incident Data	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**Grand Total**
Oil Spill	-	-	-	-	1	-	-	-	-	-	-	1
Grounding	1	1	1	-	-	1	1	1	1	2	-	9
Theft		1	3	6	-	3		1		9	2	25
Collision	4	2	5	1	5	8	3	5	5	10		48
Cargo Loss	-	2	-	3	3	-	-	-	-	-	-	8
Propulsion Failure	-	1	1	2	3	2	-	-	-	-	-	9
Cargo Damage	-	1	1	-	1	-	-	-	-	1	-	4
Structural Failure	-	1	-	8	1	3	-	-	6	-	-	19
Machinery Failure	-	-	-	1	-	-	-	-	-	-	-	1
Anchor Loss	-	1	3	1	2	2	4	1	3	8		25
Crew-Related Incident	-	-	1	2	1	2	-	-	-	1	1	8
Struck by Another Vessel	-	-	-	4	-	-	3	-	2	3	1	13
Grand Total	5	10	15	28	17	21	11	8	17	34	4	170

III. Results and Discussion

A. Analysis of Accident Trends and Patterns

Based on the incident data of tug and barge vessels operated by Company XYZ during the period 2015–2025, a total of 170 accident cases were recorded, as shown in **Table 2** and illustrated in **Figures 2-3**.

The annual accident data from 2015 to 2025 demonstrate fluctuating trends characterized by several notable increases and declines. The number of incidents rose steadily from 5 cases in 2015 to 28 cases in 2018, reflecting a rapid increase in operational risks or reporting during the early years. This was followed by a decline in 2019 with 17 incidents, before rising again to 21 incidents in 2020. A subsequent downward trend occurred between 2021 and 2022, reaching one of the lowest levels at 8 incidents in 2022, which may indicate improvements in operational control, enhanced safety practices, or reduced operational activity. However, accidents increased again in 2023 with 17 incidents and reached the highest peak in 2024 with 34 incidents, suggesting a significant escalation in maritime risk factors. The accident pattern reflects an unstable trend with periodic spikes that may be influenced by operational intensity, human factors, and technical challenge.

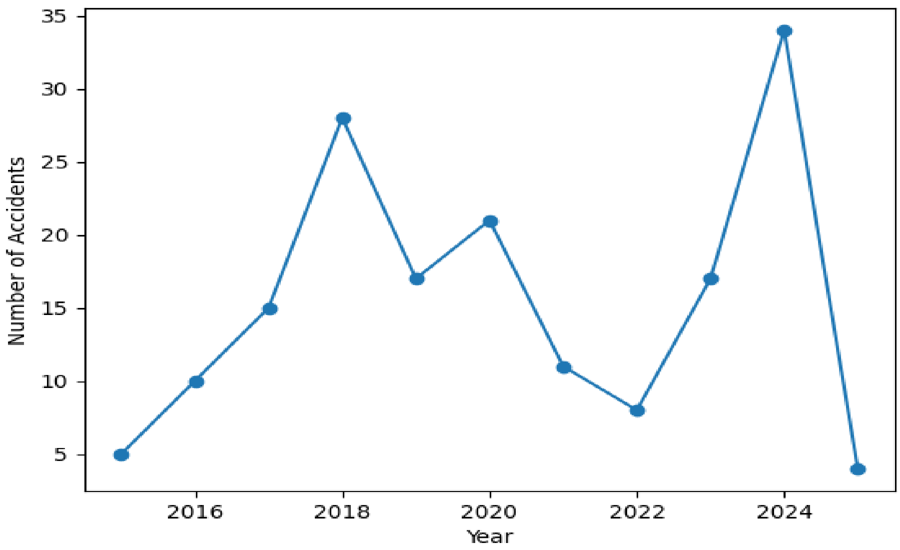

Figure 2. Number of Accidents per Year (2015-2025)

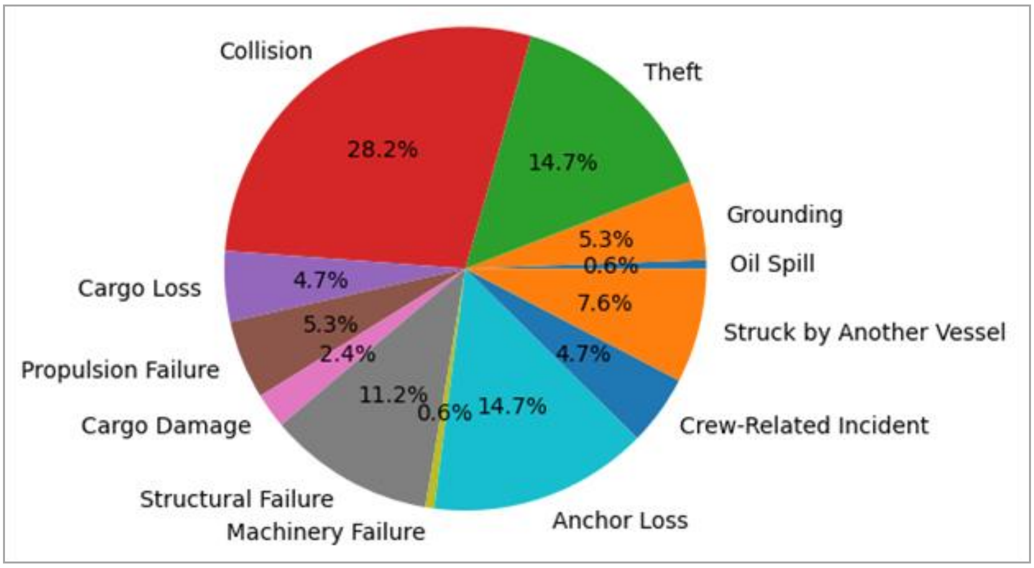

Figure 3. Percentage Distribution of Accident Types

The distribution of accident types from a total of 170 incidents reveals several dominant categories and risk patterns. Collision was the most frequent type, accounting for 48 cases (approximately 28.2%), highlighting significant navigational risks and operational coordination challenges. Theft and anchor loss each contributed 25 cases (around 14.7%), indicating recurring operational vulnerabilities and maritime security issues. Structural failure accounted for 19 incidents (approximately 11.2%), suggesting concerns related to vessel condition, aging structures, or maintenance practices. Incidents categorized as Struck by another vessel totaled 13 cases (about 7.6%), further emphasizing traffic density and situational awareness risks. Moderate categories included grounding, propulsion failure, cargo loss, and crew-related Incidents, each reflecting a combination of operational, technical, and human-factor challenges. Meanwhile, minor categories such as oil spills and machinery failure showed very low occurrence (approximately 0.6%), indicating lower frequency events but with potentially significant operational and environmental consequences when they occur.

The accident characteristics from 2015–2025 demonstrate that maritime incidents are primarily influenced by operational and human-related risks, with technical and environmental factors contributing to a lesser but still important extent. The sharp increase in 2024 signals the need for enhanced preventive strategies, including crew training, traffic monitoring, maintenance systems, and operational risk management.

B. Analysis of Accident Causes Using the AHP Method

Based on incident data, field observations, and expert interviews (senior captains, safety officers, and operational management personnel), four main criteria were identified as key contributors to vessel accidents:

1) Human Factors (Human Error)
   Crew-related errors such as fatigue, miscommunication, and violations of Standard Operating Procedures (SOP).
2) Technical Factors
   Technical issues include machinery failures, a malfunctioning navigation system, and aging vessels.
3) Environmental Factors
   External conditions such as adverse weather, strong currents, and low visibility.
4) Procedural Factors
   Failures in implementing safety procedures, including incomplete ISM Code documentation and insufficient crew training.

Each criterion contributes differently to accident risk levels. Therefore, to obtain a more detailed and structured analysis, each main criterion was further decomposed into several sub-criteria, illustrated in **Figure 4** as an AHP hierarchical diagram.

This hierarchical structure enables a quantitative priority analysis using the Analytic Hierarchy Process (AHP), based on expert input collected through pairwise comparison questionnaires. The method allows for the determination of weights and ranking of accident causes according to their relative importance. As a result, mitigation strategies can be more effectively focused on the most influential and operationally relevant factors, improving safety management and reducing accident risks in maritime operations.

After the questionnaire data from respondents were collected, pairwise comparison assessments for each element were carried out using the Analytic Hierarchy Process (AHP) method. This process applies Saaty's 1–9 scale to compare two elements at a time. Based on the collected data, four main criteria were evaluated: Human Factors (H), Technical Factors (T), Environmental Factors (E), and Procedural Factors (P). AHP questionnaire results from respondents are shown in **Table 3**.

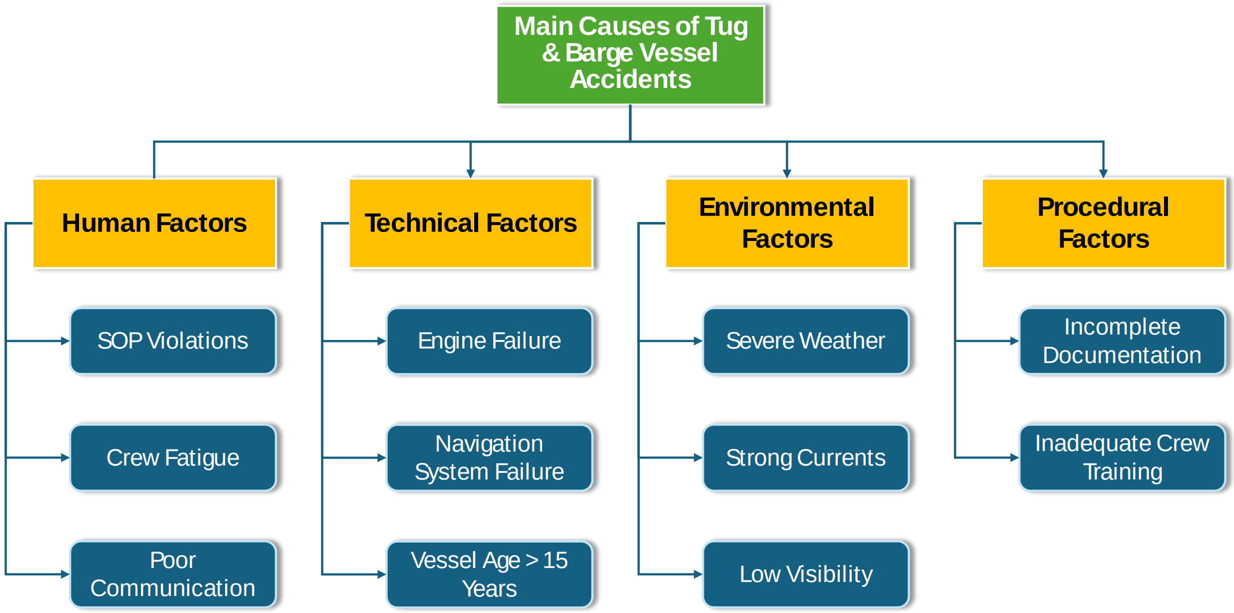

Figure 4. AHP Hierarchical Diagram

TABLE 3.
AHP QUESTIONNAIRE RESULTS FROM RESPONDENTS

RESPONDENT	H_T	H_E	H_P	T_E	T_P	E_P
Respondent 1	3	5	7	3	4	2
Respondent 2	3	5	6	3	4	3
Respondent 3	3	5	7	2	6	3
Respondent 4	3	5	6	3	6	4
Respondent 5	3	5	6	3	5	4
Respondent 6	4	5	6	4	5	3
Respondent 7	4	6	6	2	5	2
Respondent 8	2	6	6	4	5	4
Respondent 9	2	4	9	4	5	2
Respondent 10	2	4	9	2	5	3

1) Step 1: Construction of the Pairwise Comparison Matrix.

The average values obtained from 10 respondents for each comparison are as follows:

- Human vs Technical (H_T) : 3
- Human vs Environmental (H_E) : 5
- Human vs Procedural (H_P) : 7
- Technical vs Environmental (T_E) : 3
- Technical vs Procedural (T_P) : 5
- Environmental vs Procedural (E_P) : 3

The Pairwise Comparison Matrix (4x4) is constructed based on the rounded values above. This matrix represents the core component of the AHP method and follows the reciprocal principle of AHP, where AHP: $Aij = 1/Aji$.

2) Step 2: Matrix Normalization

Each element in the pairwise comparison matrix is divided by the total of its respective column to obtain the normalized matrix. The column totals are shown in **Table 5** and calculated as follows:

- Human column total: 1+1/3+1/5 +1/7 = 1.676
- Technical column total: 3+1+1/3+1/5 = 4.533
- Environmental column total: 5+3+1+1/3= 9.333
- Procedural column total: 7+5+3+1=16

After that, summing the values of each column in the matrix for normalization purposes, as shown in **Table 6**.

3) Step 3: Calculation of Priority Weights

The priority weights are calculated by taking the average value of each row in the normalized matrix. This process determines the relative importance of each criterion by summarizing its comparative performance against all other criteria. The priority weights results are shown in **Table 7.**

4) Step 4: Consistency Test

The consistency test is conducted to ensure that the pairwise comparison judgments made by respondents are logically consistent and reliable within the Analytic Hierarchy Process (AHP). This step involves calculating the Consistency Index (CI) and Consistency Ratio (CR) by comparing the maximum eigenvalue (λmax) of the matrix with the Random Index (RI) value, and the result is shown in **Table 8**.

TABLE 4.
PAIRWISE COMPARISON MATRIX

4 x 4 Matrix	Human	Technical	Environmental	Procedural
Human	1	3	5	7
Technical	0.333	1	3	5
Environmental	0.200	0.333	1	3
Procedural	0.143	0.200	0.333	1

TABLE 5.
COLUMN SUMMATION RESULTS

4 x 4 Matrix	Human	Technical	Environmental	Procedural
Human	1	3	5	7
Technical	0.333	1	3	5
Environmental	0.200	0.333	1	3
Procedural	0.143	0.200	0.333	1
Total	1.676	4.533	9.333	16

Based on the calculations, the Consistency Ratio (CR) is 0.043, which is less than 0.10. Therefore, the pairwise comparison matrix is considered consistent, and the AHP results are acceptable and reliable for further analysis and decision-making. This indicates that the judgments provided by the respondents are logically consistent, and the resulting priority weights can be confidently used to determine the dominant factors contributing to maritime accidents.

TABLE 6.
COLUMN SUMMATION RESULTS

Normalized Matrix	Human	Technical	Environmental	Procedural
Human	0.5966	0.6618	0.5357	0.4375
Technical	0.1989	0.2206	0.3214	0.3125
Environmental	0.1193	0.0735	0.1071	0.1875
Procedural	0.0852	0.0441	0.0357	0.0625

TABLE 7.
PRIORITY WEIGHTS RESULTS

Normalized Matrix	Human	Technical	Environmental	Procedural	Priority Weight
Human	0.5966	0.6618	0.5357	0.4375	56%
Technical	0.1989	0.2206	0.3214	0.3125	26%
Environmental	0.1193	0.0735	0.1071	0.1875	12%
Procedural	0.0852	0.0441	0.0357	0.0625	6%

TABLE 8.
AHP PERCENTAGE

	Priority Weight	Percentage
Human	0.5579	55.8%
Technical	0.2633	26.3%
Environmental	0.1219	12.2%
Procedural	0.0569	5.7%

The results indicate that the Human factor has the highest relative weight (55.8%) in influencing the analyzed system, followed by technical factors (26.3%), Environmental factors (12.2%), and Procedural factors (5.7%). Interpretation: The human factor receives the highest weight due to the dominant role of crew members in decision-making processes, violations of standard operating procedures (SOPs), and the challenging working conditions at sea. This finding is consistent with observational results and with Reason's (1990) theory, which states that human error is one of the primary causes of maritime accidents.

C. Mitigation Recommendations

This section examines the direct and indirect impacts of tug and barge vessel accidents on company operations, based on operational records, insurance data, and internal performance reports. The impact of accidents on company operations is described as follows:

1) Material Losses
   Total insurance claims reached IDR 1.2 billion (2020–2024), with the highest loss around IDR 350 million (2024).
2) Operational Delays
   An average downtime of 3–7 days per incident disrupted the coal supply chain to power plants (PLTU)
3) Environmental Impact
   Five cases of fuel leakage and cargo fires caused marine pollution (e.g., coal cargo fire on TB Iris, 2016).
4) Corporate Reputation
   Approximately 15% of customers submitted complaints due to delivery delays (Internal Data, 2023).

D. Impact of Accidents on Company Operations

Based on the accident trend analysis and AHP priority results, several strategic mitigation measures are proposed to reduce operational risks and improve maritime safety performance. These recommendations focus on strengthening human competency, enhancing technical reliability, improving navigational awareness, and reinforcing procedural compliance. The objective is to minimize accident frequency, reduce operational disruptions, and support sustainable and safe tug and barge operations within the company. The mitigation recommendation is described as follows:

1) Crew Training Enhancement
   Conduct emergency maneuver simulations and safety workshops based on the International Safety Management Code (ISM Code) to improve decision-making skills and operational awareness.
2) Periodic Vessel Maintenance
   Replace anchor wires and perform propeller inspections every six months to reduce technical failures and unexpected downtime.
3) Installation of Navigation Technology: Implement real-time GPS monitoring and early warning systems to enhance situational awareness and prevent collisions.
4) Annual Safety Audits: Evaluate SOP compliance, review operational practices, and strengthen the overall safety culture within company operations.

IV. CONCLUSION

This study examined the causes, characteristics, and operational impacts of tug and barge vessel accidents at Company XYZ during 2015–2024 and established mitigation priorities using the Analytic Hierarchy Process (AHP). The analysis of 170 accident cases confirms that although tug and barge operations are vital for Indonesia's maritime logistics due to their efficiency and flexibility, they remain highly exposed to safety risks. The findings demonstrate that human factors are the dominant contributor to accidents, accounting for 55.8%, followed by technical factors (26.3%), environmental factors (12.2%), and procedural factors (5.7%), with a consistency ratio of 0.043 indicating reliable expert judgment and acceptable analytical consistency. Beyond causation, accidents were shown to significantly influence company performance through material losses, insurance claims, operational disruptions averaging three to seven days per incident, and environmental consequences such as fuel spills and onboard fires, all of which directly affect efficiency, supply chain continuity, and corporate reputation. These results highlight that accident prevention must be treated as a strategic operational priority rather than solely a technical or compliance issue. In response to the research objectives, mitigation efforts should focus primarily on strengthening human performance through enhanced training, effective communication, fatigue management, and strict adherence to standard operating procedures, while also reinforcing technical reliability through preventive maintenance and improved navigation systems. Environmental awareness and procedural discipline must be integrated into daily operational practices to ensure a comprehensive safety culture. The application of AHP in this study provides a structured and practical decision-support framework that enables maritime operators to allocate resources based on prioritized risk factors, supporting more effective safety management and long-term operational sustainability in tug and barge vessel operations within Indonesia's maritime sector.

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