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Safety Analysis of Ferry Passenger Vessels Using the Formal Safety Assessment (FSA) Method

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Abstract**—** Although maritime regulations have been implemented in Indonesia, ship accidents remain a major concern. In general, these accidents are mainly caused by human failure. Based on accident data, the number of ferry operational accidents showed an increasing trend during the period of 2020–2024. Therefore, this study aims to identify appropriate solutions to reduce the risk of ship accidents by integrating Formal Safety Assessment (FSA) and the Analytic Hierarchy Process (AHP). Risk assessment was conducted by evaluating the frequency and consequences of each accident type, which showed that sinking cases have the highest risk level, while collision cases are the most frequently occurring accidents. Both accident types were further analyzed using the SHIELD taxonomy to identify their contributing factors in greater detail, enabling the development of suitable Risk Control Options (RCOs) for each accident scenario. The proposed RCOs were evaluated using the AHP method based on four criteria, namely cost, applicability, frequency effectiveness, and severity consequences, and were subsequently assessed using the Cost–Benefit Analysis approach within the FSA framework. For sinking accidents, the recommended RCOs are the implementation of a loading sequence checklist, mandatory briefings for vehicle drivers, and documentation and dissemination of lessons learned to all personnel. Based on expert judgment, these measures are expected to reduce the accident frequency to approximately one case every seven years and decrease the accident consequences by up to 27.72%. For collision accidents, the recommended RCOs are the implementation of an environmental condition checklist before maneuvering, mandatory berthing briefings prior to maneuvering, and enhanced visual awareness of critical areas surrounding the vessel. These measures are expected to reduce collision accidents to 21 cases within five years and decrease the consequences of each accident by up to 15.54%.

*Keywords***—**Analytical Hierarchy Process, Formal Safety Analysis, Risk Assessment, SHIELD Taxonomy

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I. INTRODUCTION

Sea transportation, as one of the main modes of inter-island connectivity in Indonesia, must comply with certain standards to ensure security and safety for both passengers and logistics. Law of the Republic of Indonesia Number 17 of 2008 concerning Shipping states that the implementation of the ISM Code 1998 and ISPS Code 2002 regulates various aspects of maritime safety. These aspects include the materials used, ship construction processes, building specifications, machinery and electrical systems, ship stability, as well as ship arrangements and other supporting equipment [1]. However, ship accidents still occur frequently in Indonesia. The main factors contributing to ship accidents include inadequate marine navigation systems and human error [2].

One such accident occurred on June 29, 2021, when KMP Yunicee was berthed at the movable bridge (MB) 1 dock of Ketapang Ferry Port with the port side alongside and the bow ramp lowered onto the MB. On average, Yunicee operated eight trips per day between Ketapang and Gilimanuk. At the time of the incident, the vessel was conducting its fourth trip and had sailed more than 2 nautical miles while remaining idle awaiting berthing instructions from Local Port Service 4 (LPS) at Gilimanuk Ferry Port. Suddenly, the weather conditions deteriorated, and a strong southward current combined with winds blowing from the southeast caused the vessel to list. Sea waves became increasingly rough. The captain, second officer, and helmsman on the bridge noticed that the vessel began to heel to port. Seawater entered through the freeing ports, causing the ship to tilt to nearly 10 degrees. As the inclination continued to increase, passengers and crew members jumped into the sea. The vessel eventually capsized to port, and within less than five minutes, the keel was above the water surface. This accident resulted in 11 fatalities and 13 missing persons [3].

In addition, data obtained from PT X indicate that the average annual increase in ship accidents, particularly during the 2020–2024 period, demonstrates an alarming trend in maritime safety [4]. These incidents highlight the importance of implementing effective methods to improve safety and reduce the risk of ship accidents. Based on these accident data, a method is required that can enhance ship safety probability and minimize the risk of maritime accidents.

Accordingly, the researchers conducted a mapping study using the Scopus Database with the assistance of the VOSviewer application. The study identified three dominant keywords within the same cluster related to improving ship safety probability and reducing ship accident risk, namely the Formal Safety Assessment (FSA) method, Fault Tree Analysis (FTA), and Bayesian

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Network. The application of the FSA method has been widely implemented in various types of vessels, including passenger ships [5][6], cargo ships [7][8], and cruise ships [9]. These studies demonstrate that FSA is capable of identifying hazards within ships and their navigation systems, conducting Cost Benefit Analysis (CBA) affecting ship operations, and assessing measurable ship safety levels.

The FSA method is also frequently combined with other methods to provide a more comprehensive explanation in hazard identification. The integration of FSA with Bayesian theory enables detailed hazard identification in ship navigation systems [10][11]. Meanwhile, the collaboration of FSA with Fault Tree Analysis (FTA) demonstrates that FSA enhances FTA in decision-making processes and facilitates the integration of risk matrices in seismic vessel operations [12][13]. FSA was selected as the research method because it encompasses stages for improving ship safety and reducing accident risks through hazard identification [14][15].

Although many methods have been integrated with FSA, the researchers have not found any methodological collaboration between FSA and the Analytical Hierarchy Process (AHP). One advantage of AHP is its structured evaluation process and its ability to produce more consistent results in the form of composite scores based on the Consistency Index (CI) and Consistency Ratio (CR) [16][17].

In this study, the researchers sought to initiate a systematic framework for addressing the increasing trend of maritime accidents by applying the Formal Safety Assessment (FSA) methodology, which has been widely adopted across various ship types within the maritime industry, in combination with the Analytic Hierarchy Process (AHP) for decision-making. AHP itu sendiri memang sebuah teknik yang sering diintegrasikan dengan teknik yang lain bahkan dalam sebuah pemrograman, meskipun tidak dengan FSA. [18]

The integration of these two methods enables a comprehensive evaluation of alternative Risk Control Options (RCOs), ensuring that the selected measures are not only economically beneficial but also practical to implement, cost-effective, and capable of reducing both the frequency and severity of maritime accidents. This integrated framework provides a structured and quantitative basis for supporting safety-related decision-making and may serve as a valuable reference for future risk management practices in the maritime sector.

A. Formal Safety Assessment

The formulation of the Formal Safety Assessment (FSA) method was first studied in 1988 by Froome and Monahan. The initial objective of developing the FSA method was to illustrate the role of formal methods in the development of safety-critical software systems within the industry [19]. Subsequently, the FSA method was tested for improving safety in offshore coastal areas. Several studies demonstrated that the FSA method could be effectively applied as an approach to enhance safety within the maritime sector [20].

Formal Safety Assessment (FSA) is a structured and comprehensive approach used in the maritime industry to systematically evaluate and manage risks associated with ship operations. Fundamentally, FSA aims to enhance maritime safety by identifying potential hazards, assessing their consequences, and proposing appropriate risk control measures.

1) *Hazard Identification*: The identified hazards and related scenarios relevant to the issue under consideration should be ranked to determine their priorities and to eliminate scenarios considered insignificant. An assessment of the frequency and consequences of each scenario outcome should also be conducted.
2) *Risk Assessment*: Risk analysis aims to thoroughly investigate the causes and initiating events, as well as the consequences, of significant accident scenarios identified during the hazard identification process.
3) *Risk Control Option*: This stage aims to develop risk control options that address existing risks as well as risks arising from new technologies or new operational and management methods.
4) *Cost-Benefit Analysis*: Step 4 aims to identify and evaluate the benefits and costs involved in implementing each Risk Control Option (RCO) that has been identified and selected in the previous step.
5) *Recommendation*: The final step of Formal Safety Assessment is to determine the most suitable Risk Control Option (RCO) based on the best balance between safety benefit and implementation cost, typically evaluated using the Benefit-Cost Ratio (BCR). The selected recommendation should provide the most effective measure for reducing the risk of accidents and improving operational safety.

B. SHIELD Taxonomy

The SHIELD project is an initiative aimed at developing a safety learning taxonomy and database that can be applied within the transportation sector, particularly in aviation and maritime industries. Its framework continues to employ a systemic approach to analyze accidents caused by human error. [21]

1) *Unsafe acts*: describe actions or conditions that deviate from planned procedures and contribute to failures or accidents. These acts include perception failures, planning and decision-making errors, intentional deviations from procedures, improper response execution, and communication failures. Such conditions may occur when operators fail to detect information accurately, make incorrect or delayed decisions, intentionally bypass procedures, execute actions improperly, or communicate ineffectively with other actors involved.
2) *Preconditions*: refer to factors that influence operator performance during operations. These conditions include physical environment, equipment and workplace conditions, interpersonal communication, team or group dynamics, misperception, awareness, memory, mental workload, personal factors, physiological condition, drug and nutrition effects, as well as competence, skills, and capability. Such factors may interfere with operator perception,

communication, decision-making, physical and mental performance, and overall operational effectiveness.

TABLE 1.
VALUE OF RANDOM CONSISTENCY INDEX [17]

	n = 1	n = 2	n = 3	n = 4	n = 5	n = 6	n = 7	n = 8	n = 9	n = 10	n = 11	n = 12
RCI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.58

3) *Operational leadership*: refers to the influence of leadership and management practices on operational performance and safety. This includes personnel leadership, operations planning, and task leadership. Inadequate leadership may contribute to failures through insufficient supervision, poor risk assessment, inadequate staffing, lack of safety enforcement, ineffective feedback, and allowing unsafe practices or unqualified personnel during operations.
4) *Organisation*: refers to the influence of organisational and company-related factors on operational safety. These factors include organisational culture, safety management, resources, and economic or business conditions. Weak safety culture, inadequate safety management systems, limited resources, insufficient training, and economic or operational pressures may negatively affect safety performance and increase the likelihood of accidents or failures.

C. *Analytical Hierarchy Process*

The Analytic Hierarchy Process (AHP) is one of the multi-criteria decision-making methods developed by Thomas L. Saaty [17]. As the name implies, this theory explains the process of solving complex problems in a more structured and systematic manner through the application of a hierarchical method. Hierarchy is used as a representative structure in decision-making for a particular problem. Through the hierarchical method, a problem is divided into major groups, which are then further broken down into smaller groups, forming different levels or layers within the hierarchy [22].

TABLE 2.
PASSENGER FERRY SHIP ACCIDENTAL CASES AT PT. X

Year	Accident Case							
	Fire Cases	Grounding	Collision	Sinking	Heel	Leakage	Cargo Drowning	Cargo Overturning
2020	0	1	6	0	0	3	0	0
2021	0	1	10	0	0	0	0	0
2022	2	2	5	1	0	1	1	0
2023	2	2	8	0	0	1	0	1
2024	4	1	16	0	1	2	0	1
TOTAL	8	7	45	1	1	7	1	2

The Analytic Hierarchy Process (AHP) requires the establishment of evaluation criteria to represent the perspectives used in the decision-making process. These criteria are determined based on expert judgment from individuals with extensive knowledge and experience in the relevant field, enabling the relative importance of each criterion to be assessed. Experts subjectively evaluate the significance of each criterion using a predefined rating scale, allowing the decision-making perspectives to be systematically prioritized. Subsequently, each criterion is assigned a weight through the AHP procedure. These weights are then utilized within a Multi-Criteria Decision-Making (MCDM) framework to evaluate and rank the available alternatives according to their overall performance across multiple decision criteria.[23]

The result of this method is a set of alternative options. Based on this explanation, AHP is closely related to decision-making. Decision-making is the process of selecting one alternative from several available options based on multiple criteria [18]. In the decision-making process, multiple criteria are often considered, resulting in several alternative options that may be used. The final outcome of the AHP process is the prioritization of the available alternatives, where these priorities can be used to determine the best alternative [24].

The purpose of using the Analytic Hierarchy Process (AHP) method in risk management is to ensure the provision of the required information and to redesign risk management principles by integrating them into ship management practices. The methodology is used to redesign current risk management requirements and to develop an advanced management system aimed at reducing potential hazards.

The Analytic Hierarchy Process (AHP) can be used to obtain ratio scales from pairwise comparisons. AHP is widely recognized as one of the most effective methods for explaining decision-making processes in complex problems [25]. The steps or procedures of AHP that can be carried out are as follows:

1) Define the problem and determine the desired solution.
2) Design a hierarchical structure starting from the main objective, followed by the criteria, and ending with several alternative options.
3) Determine the elements to be compared in order to form pairwise comparisons along with the assessment scale used to measure them, after which the total number of comparisons can be determined.
4) Construct a pairwise comparison matrix that describes the relative contribution or influence of

each element toward the objective or criteria at the higher level. The comparison is carried out based on the judgement of the decision-maker by considering the priority level of each element relative to the compared element.

5) Make decisions by considering the consistency value used in the evaluation process.
6) Determine the Consistency Index (CI) value of the hierarchy using the following formula.

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

Where,
n is the quantity of the used criteria. Principal Eigen value λ_{max} obtained from the summation of products between each element of Eigen vector and the sum of columns of the reciprocal matrix.

TABLE 3.
FREQUENCY INDEX OR LOGARITHMIC PROBABILITY [14]

FI	Frequency	Definition	F per Year
7	Frequent	Likely to occur once per month on one ship	10
5	Reasonably Probable	Likely to occur once per year in a fleet of 10 ships, i.e. likely to occur a few times during the ship's life	0.1
3	Remote	Likely to occur once per year in a fleet of 1,000 ships, i.e. likely to occur in the total life of several similar ships	10^{-3}
1	Extremely Remote	Likely to occur once in the lifetime (20 years) of a world fleet of 5,000 ships	10^{-5}

TABLE 4.
SEVERITY INDEX OR LOGARITHMIC CONSEQUENCE [14]

SI	Severity	Effects On Human Safety	Effects On Ship	S Equivalent Fatalities
1	Minor	Single or Minor Injuries	Local Damage	0.01
2	Significant	Multiple or severe Injuries	Non severe damage	0.1
3	Severe	Single Fatality or multiple severe Injuries	Severe damage	1
4	Catasthrophic	Multiple Fatalities	Total loss	10

7) Determine the Consistency Ratio (CR) of the hierarchy using the following equation.

$$CR = \frac{CI}{RCI} \quad (2)$$

Where,
CI is the consistency index that obtained from 6th step and RCI is the random consistency index that can be seen at Table 1. This value is depend on the quantity of the used criteria.

8) Check the consistency of the hierarchy. If the CR value is less than 0.1, the pairwise comparison values in the criteria matrix are considered consistent. However, if the CR value is greater than or equal to 0.1, the pairwise comparison values in the criteria matrix are considered inconsistent. Therefore, if inconsistency occurs, the values in the pairwise comparison matrix must be reassessed and revised.

II. METHOD

A. Passenger Ship Accident Data

The accident data used in this study were obtained from PT. X, a ferry shipping company that focuses on providing crossing transportation services in Indonesia. The collected data consist of accident cases that occurred within the company during the period from 2020 to 2024.

The collected data are presented in Table 2, which shows eight classifications of accidents that occurred during the four-year period. These include 8 fire incidents, 7 grounding incidents, 45 collision cases, 1 sinking incident, 1 heeling incident, 7 leakage incidents, 1 case of cargo falling overboard, and 2 cases of cargo overturning. In total, 72 accidents occurred on passenger vessels operated by PT. X during the 2020–2024 period.

B. Hazard Identification – Frequency Index

One way to prioritize the identified hazards (accident cases) is by evaluating the initiating events along with their frequency and consequences through the use of indices that represent the conditions and the hazards themselves. The logarithmic probability or frequency index used in this study follows the r ange defined in Table 3.

Table 3 presents four classifications of Frequency Index (FI) based on the likelihood of accident occurrence, ranging from FI = 1 to FI = 7. Intermediate values, such as FI = 2, are assigned when the accident frequency falls within the range between 10^{-5} and 10^{-3}. This approach also applies to the other intermediate index values. With the type of data obtained, the data needs to be converted into a form that can be evaluated by the frequency index parameter; therefore, Equation 4 is used.

$$Freq.\ Probability\ (F) = \frac{Qty.Accident}{Total\ Voyage} \quad (4)$$

C. Hazard Identification – Severity Index

Hazard identification in ship accidents cannot be adequately performed solely by describing the frequency of accident occurrences. In some cases, ship accidents may have highly significant consequences despite occurring infrequently. Therefore, Table 4 presents the

Severity Index (SI) as the logarithmic representation of consequences.

As shown in Table 4, severity is classified into four severity index levels ranging from 1 to 4: Minor, Significant, Severe, and Catastrophic. These classifications are determined based on two main aspects, namely the impact of an incident on human safety and its impact on the vessel or other property. Based on these two aspects, the severity level of an accident can be evaluated.

D. Hazard Identification – Risk Index

The determination of the Risk Index is one method used to prioritize ship accident events. This study applies the method to evaluate the types of accidents that present the highest level of risk based on both the number of accident occurrences and their severity level. The equation used to obtain the Risk Index, or the logarithmic version of risk, is presented in the following equation based on Severity Index (SI) and Frequency Index (FI). [13]

$$Risk\ Index\ (RI) = SI + FI \tag{3}$$

Alternatively, a simpler representation can be shown using the risk matrix adopted and suggested from previous studies, as presented in Table 5. In this matrix, the Risk Index value is influenced by the Severity Index (rows) and the Frequency Index (columns), resulting in the same Risk Index value as obtained from Equation (3).

TABLE 5.
RISK INDEX OR LOGARITHMIC OF RISK [14]

RISK INDEX (RI)							
SI	Frequency Index (FI)						
	1	2	3	4	5	6	7
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
2	**3**	**4**	**5**	**6**	**7**	**8**	**9**
3	**4**	**5**	**6**	**7**	**8**	**9**	**10**
4	**5**	**6**	**7**	**8**	**9**	**10**	**11**

E. Risk Assessment

Risk analysis aims to thoroughly investigate the causes and initiating events, as well as the consequences, of significant accident scenarios identified during the hazard identification process. In examining these aspects, this study employs an additional method to describe the initiating events and causes of the accident data obtained, namely the SHIELD Taxonomy approach.

Using this method, the causes of each accident event can be analyzed through four systemic approaches, including unsafe acts, preconditions, operational leadership, and organisational factors. This approach also facilitates the identification of appropriate Risk Control Options (RCOs) based on the underlying causes of the accidents.

F. Risk Control Option (RCO)

The search for Risk Control Options (RCOs) was carried out as a follow-up to the ship accident risk assessment that had been conducted. These risk control measures may include the implementation of new technologies, new standards, or improved management methods. The formulation of the RCOs focused on two types of accidents, namely the most frequently occurring accidents and the accidents with the highest ranking based on the mapped risk index.

G. AHP Assessment on RCO

The RCO assessment was conducted by evaluating the Risk Control Options using the Analytic Hierarchy Process (AHP) method. This method was selected because it supports multi-criteria decision-making, which is suitable for determining the most appropriate RCOs.

Unlike the conventional FSA approach that mainly emphasizes Cost-Benefit Analysis, this study considers additional criteria, including the applicability of each RCO, its effectiveness in reducing accident frequency, and its effectiveness in reducing accident consequences. Therefore, the proposed solutions are expected not only to focus on cost effectiveness and benefits, but also to consider implementation capability and more specific operational impacts.

The inclusion of specific impact criteria aims to capture the risk concept defined within the FSA framework, where risk is determined not only by frequency but also by consequence or severity. Some accidents require solutions that primarily reduce the frequency of occurrence, while others require measures that minimize the severity when accidents occur.

Accordingly, these criteria were adopted in this study, and the weighting of each criterion for different accident types was determined with the involvement of experts in the maritime transportation field. Since the study focuses on two selected accident categories, expert judgement was used to obtain weighting models that are more representative of actual operational conditions in the shipping industry.

In addition to determining the comparative weights of each criterion, the evaluation of each RCO against the assessment criteria was also carried out through expert judgement. This assessment involved not only academic experts but also personnel directly associated with PT. X, in order to better reflect implementation feasibility and provide a more objective evaluation of effectiveness within the context of the study.

H. Cost-Benefit Analysis (CBA)

The costs and benefits of all Risk Control Options (RCOs) need to be elaborated. This is carried out in accordance with the FSA method to estimate and compare the cost-effectiveness of each risk control option based on the benefits gained from the resulting risk reduction divided by the total cost required for implementing the risk control measure, as presented in Equation (4).

$$Benefit\ Cost\ Ratio\ (BCR) = \frac{Benefit}{Implementation\ Cost} \quad (4)$$

I. CBA-AHP Final Assessment

The final step of this study is to assess all Risk Control Options (RCOs) based on the results of the Cost Benefit Analysis (CBA) and the Analytical Hierarchy Process (AHP). In this study, CBA and AHP are considered to have equal importance; therefore, their results are combined using a 50:50 ratio. The output of this final assessment consists of the three best Risk Control Options for ship accident cases with the highest risk level and the three best Risk Control Options for ship accident cases with the highest total frequency, as determined by the combined CBA-AHP evaluation.

III. Results and Discussion

A. Frequency Index Calculation

In determining the frequency index for each type of accident per year, it is necessary to calculate the probability of accident occurrence. In accordance with the definition of probability itself, the accident data obtained must be compared with the total number of voyages conducted by PT. X each year.

Table 6 presents the total number of voyages conducted annually. Based on these data, the frequency probability value (F) for each year can be calculated using Equation (4).

From the data presented in Table 6 and Equation (4), the frequency probability value (F) can be obtained. These values are then compared with Table 3 to determine the Frequency Index (FI) classification based on the probability of accident occurrence (F), as presented in Table 7.

Table 6.
Total Operational Voyage Data PT. X

2020	2021	2022	2023	2024
44,375	43,510	43,510	47,255	49,847

Table 7.
Passenger Ferry Ship Accidental Frequency Probability (F) and Frequency Index (FI)

	Fire Cases		Grounding		Collision		Sinking		Heel		Leakage		Cargo Drowning		Cargo Overturning	
	F	FI	F	FI	F	FI	F	FI	F	FI	F	FI	F	FI	F	FI
2020	-	1	$2.3E^{-05}$	3	$1.4E^{-04}$	3	-	1	-	1	$6.8E^{-05}$	3	-	1	-	1
2021	-	1	$2.3E^{-05}$	3	$2.4E^{-04}$	3	-	1	-	1	-	1	-	1	-	1
2022	$4.6E^{-05}$	3	$4.6E^{-05}$	3	$1.2E^{-04}$	3	$2.3E^{-05}$	3	-	1	$2.3E^{-05}$	3	$2.3E^{-05}$	3	-	1
2023	$4.2E^{-05}$	3	$4.2E^{-05}$	3	$1.7E^{-04}$	3	-	1	-	1	$2.1E^{-05}$	3	-	1	$2.1E^{-05}$	3
2024	$8.0E^{-05}$	3	$2.0E^{-05}$	3	$3.2E^{-04}$	3	-	1	$2.0E^{-05}$	3	$4.0E^{-05}$	3	-	1	$2.0E^{-05}$	3

B. Severity Index Calculation

Hazard identification in ship accidents cannot rely solely on describing the frequency of accident occurrences. In certain cases, ship accidents may produce significant impacts even though their frequency of occurrence is relatively low. Therefore, at this stage, hazard identification is continued by describing the impacts or consequences of each type of accident.

In this study, since the impacts of each accident type had already been described in the accident reports, the severity index for each accident recorded by PT. X during the 2020–2024 period could be assessed directly. The determination of the Severity Index (SI) was based on the criteria presented in Table 4.

Each accident record was classified along with its chronology, causes, and impacts on both the environment and human safety. This process was carried out for every accident case based on the available data. At the end of the appendix, a brief summary of the Severity Index (SI) classification for each accident type during the 2020–2024 period is provided, with the cases grouped according to accident category. For each accident type per year, the SI values from all accident cases occurring in that year were averaged. This process produced a representative Severity Index that was used in the subsequent analysis.

Table 8 presents a summary of the averaged Severity Index values for each type of accident by year, based on all accident cases occurring within the respective year. From the presented data, it can generally be observed that the severity levels of accidents occurring at PT. X during the 2020–2024 period mostly fall within the minor classification. The highest severity level was identified in the ship sinking accident that occurred in 2023, which obtained a severity index of 3, classified as severe.

C. Risk Index Calculation

The next step after hazard identification in ship accidents is to assess the risks associated with those hazards. The level of risk is influenced by both the frequency of accident occurrence and the severity of the accident consequences. These two aspects cannot be separated in risk assessment because, as stated in MSC-MEPC.2/Circ.12, accidents with low occurrence frequency but severe consequences or high casualties may still present a high level of risk.

TABLE 8.
SEVERITY INDEX (SI) OF EACH ACCIDENTAL CASE PER YEAR

Year	Accident Case							
	Fire Cases	Grounding	Collision	Sinking	Heel	Leakage	Cargo Drowning	Cargo Overturning
2020	1	1	1	1	1	2	1	1
2021	1	2	1	1	1	1	1	1
2022	2	2	1	3	1	1	1	1
2023	2	1	1	1	1	1	1	1
2024	1	1	1	1	1	1	1	1

Based on this concept, the IMO provides guidance for risk assessment by considering both accident frequency and the severity of accident consequences within the same document. The resulting risk level, or Risk Index, derived from these two factors is presented in Table 5.

Based on the risk index classification issued by the IMO, the risk level for each type of accident by year can be evaluated, as presented in Table 9. From Table 9, the overall risk levels of the accident types range from level 1 to level 5. No accident types were found to exceed risk level 5, indicating that the accident risks based on PT. X accident data remain below the midpoint of the risk index scale established by the IMO.

TABLE 9.
PASSENGER SHIP ACCIDENT RISK INDEX

	Fire Cases			Grounding			Collision			Sinking			Heel			Leakage			Cargo Drowning			Cargo Overturning		
	FI	SI	RI	FI	SI	RI	FI	SI	RI	FI	SI	RI	FI	SI	RI	FI	RI	RI	FI	SI	RI	FI	SI	RI
2020	1	1	**2**	3	1	**4**	3	1	**4**	1	1	**2**	1	1	**2**	3	2	**5**	1	1	**2**	1	1	**2**
2021	1	1	**2**	3	2	**5**	3	1	**4**	1	1	**2**	1	1	**2**	1	1	**2**	1	1	**2**	1	1	**2**
2022	3	2	**5**	3	2	**5**	3	1	**4**	3	3	**6**	1	1	**2**	3	1	**4**	3	1	**4**	1	1	**2**
2023	3	2	**5**	3	1	**4**	3	1	**4**	1	1	**2**	1	1	**2**	3	1	**4**	1	1	**2**	3	1	**4**
2024	3	1	**4**	3	1	**4**	3	1	**4**	1	1	**2**	3	1	**4**	3	1	**4**	1	1	**2**	3	1	**4**

Based on the data presented in Table 9, one accident type with the highest risk index and also the highest severity index was selected, namely ship sinking accidents. According to Table 7, the highest Frequency Index was identified in grounding and collision accidents, both having the same frequency index value of 2 throughout the 2020–2024 period. However, for further analysis, collision accidents were selected because the total number of collision cases was higher than grounding accidents, as shown in Table 2. These two accident types were then further analyzed to identify their causes and to evaluate appropriate Risk Control Options (RCOs).

D. Risk Assessment Ship Sinking

Based on the ship accident data from 2020 to 2024, there was one recorded ship sinking accident involving Vessel SKC III on October 19, 2022. The incident occurred during cargo loading and unloading operations. The *unsafe acts* associated with this accident include:

1) Failure to visually detect the vessel's inclination or the stopped truck that caused the vessel to list (Perception – internal).
2) Delayed decision-making when the vessel began to list, resulting in the incident not being handled promptly (Planning and Decision Making – internal).
3) Delayed decision-making regarding the truck movement, which contributed to the impact on the vessel (Planning and Decision Making – external).
4) Lack of communication with the truck driver regarding the danger of stopping in the middle of the ramp door during loading and unloading operations (Communication – internal).

Based on the preconditions analysis, the causes associated with this incident include:

1) Lack of attention toward the loading and unloading activities of trucks entering the vessel (Awareness – internal).
2) Forgetfulness or failure to recall the proper loading condition and sequence that should be followed (Memory – internal).
3) Insufficient experience and capability of the truck driver in understanding operational limitations and prohibited actions during vessel loading and unloading activities (Competence, Skills, and Capability – external).

From the operational leadership perspective, the causes associated with this incident include:

1) Inadequate supervision of the ongoing loading and unloading activities (Task Leadership – internal).
2) Inadequate risk assessment regarding the hazard of stopping on the ramp door during operations (Operations Planning – external).

From the organisational perspective, the causes associated with this incident include:

1) The rushed pace of operational activities led to negligence during the loading and unloading process (Economy and Business – Internal & External).
2) Limited training programs regarding mitigation measures and critical points related to vessel stability, particularly during loading and unloading operations (Resources – Internal).

E. Risk Assessment Ship Collision

Collision accidents occurring during the 2020–2024 period accounted for a total of 45 cases based on data obtained from PT. X. The analysis of accident causes was conducted using the same approach as described in Subsection III.D by applying the SHIELD Taxonomy method. From all identified causes, a summary was compiled regarding the frequency of collision accident cause categories that resulted in accidents during the 2020–2024 period, as presented in Table 10.

TABLE 10.
FREQUENCY OF ACCIDENT CAUSES OCCURRENCE

No	Accident Cause	Qty
1	Awareness External	8
2	Awareness Internal	26
3	Communication External	6
4	Culture Internal	1
5	Culture External	4
6	Economy And Business Internal	1
7	Equipment And Workplace External	1
8	Equipment And Workplace Internal	9
9	Interpersonal Communication Internal	1
10	Interpersonal Communication External	2
11	Intentional Deviation External	3
12	Memory Internal	2
13	Misperception External	1
14	Operations Planning Internal	35
15	Operations Planning External	4
16	Perception Internal	13
17	Perception External	5
18	Personal Factors External	5
19	Personnel Leadership External	4
20	Personnel Leadership Internal	1
21	Physical Environment Internal	31
22	Planning And Decision Making Internal	35
23	Planning And Decision Making External	6
24	Resources External	3
25	Resources Internal	11
26	Response Execution Internal	1
27	Safety Management External	5
28	Safety Management Internal	33
29	Task Leadership External	4
30	Task Leadership Internal	6

F. *Risk Control Options Ship Sinking*

Risk Control Options (RCOs) are control measures designed to reduce the likelihood and consequences of ship sinking accidents, particularly during vehicle loading and unloading operations. Based on the causal analysis using the SHIELD Taxonomy approach (Acts, Preconditions, Operational Leadership, and Organisation), the risk control measures are focused on engineering controls, administrative controls, and the improvement of human resource competency.

To improve the ability to detect abnormal conditions, technology-based systems are required to provide rapid and accurate warnings. The following measures can be implemented:

1) Installation of a heel/tilt alarm system on the bridge and in the loading area as an early indicator of vessel inclination. (S1)
2) Installation of CCTV systems in critical areas such as the ramp door and vehicle deck to support real-time monitoring. (S2)
3) Implementation of a loading computer or loading application to assist in accurately calculating vessel stability and cargo distribution. (S3)

These control measures aim to minimize perception failures and improve response speed toward potential hazards.

Based on the causal analysis using the SHIELD Taxonomy approach (Acts, Preconditions, Operational Leadership, and Organisation), Procedure-based controls play a key role in ensuring that loading and unloading activities are carried out in accordance with safety principles. The measures that can be implemented include:

1) Implementation of a loading sequence checklist that must be used and verified at every stage of the operation. (S4)
2) Conducting periodic inspections throughout the loading and unloading process. (S5)
3) Development and implementation of a decision matrix as a guideline for decision-making under both normal and emergency conditions. (S6)
4) Preparation of an emergency stop loading and unloading procedure as a rapid response measure when unsafe conditions occur. (S7)

These measures aim to reduce dependence on individual memory and improve operational consistency.

Besides that, Effective supervision is required to ensure that all procedures are properly implemented. Therefore, the following measures are necessary:
1) Development of ballasting procedures integrated into every stage of loading and unloading operations to maintain vessel stability. (S8)
2) Appointment or recruitment of dedicated personnel (load master/deck officer) responsible for monitoring vessel stability and load distribution. (Ss9)
3) Training and assignment of marshals or traffic control personnel in the loading and unloading area. (S10)
4) Implementation of mandatory checklist-based briefings for all truck drivers before entering the vessel. (S11)
5) Enforcement of written operational regulations along with sanctions for violations, such as prohibiting vehicles from stopping in the ramp door area. (S12)

These control measures aim to improve awareness, strengthen operational discipline, and reduce errors caused by human factors.

Competency factors are one of the key elements in preventing accidents. Therefore, the following measures are required:
1) Training for ship crews regarding vessel stability, early signs of vessel inclination, and emergency response procedures for listing conditions. (S13)
2) Development of SOP education programs for both internal and external parties (including truck drivers), particularly regarding operational limitations and critical areas. (S14)
3) Conducting periodic simulations and emergency drills to improve preparedness in handling emergency situations. (S15)

These measures aim to enhance cognitive and technical capabilities, as well as decision-making skills in critical situations.

To ensure the sustainability of risk control measures, a systemic approach is required through the following actions:
1) Periodic updates of risk assessments (HIRADC/JSA) based on incidents, near-miss events, and lessons learned. (S16)
2) Documentation and dissemination of lessons learned to all relevant personnel. (S17)
3) Evaluation and adjustment of loading and unloading schedules by considering safety aspects in order to avoid excessive operational pressure. (S18)
4) Implementation of the “safety over schedule” principle within the company’s operational policies. (S19)

This approach aims to establish a sustainable safety culture and reduce organisational pressures that may trigger negligence.

Risk control for ship sinking accidents can be enhanced through the involvement of external support, namely:
1) Shore-Based Monitoring (AIS + Emergency Tracking) during cargo loading and unloading operations. (S20)

This measure provides an additional layer of oversight beyond the ship's crew, enables the early detection of abnormal conditions during cargo handling operations, and facilitates faster communication and emergency response when indications of hazardous conditions that may affect the vessel's stability are identified.

G. Risk Control Options Ship Collision

Based on the identification and analysis of collision accident causes using the Formal Safety Assessment (FSA) approach and the classification of causal factors based on the SHIELD Taxonomy, it was found that the dominant contributing factors to collision accidents include Planning and Decision Making, Operations Planning, Safety Management, Physical Environment, and Awareness within the internal ship and company organisation.

In particular, the high contribution of physical environment factors indicates that adverse weather conditions, sudden changes in sea currents, and unanticipated tidal conditions are among the primary triggers of collision accidents. On the other hand, human-related factors such as insufficient crew awareness of surrounding conditions (for example, regarding fender positions and vessel clearance distance) as well as weaknesses in decision-making under dynamic conditions also significantly increase the risk of collisions.

Based on these conditions, several Risk Control Options (RCOs) were developed with the objective of reducing both the likelihood and consequences of collision accidents. To reduce uncertainty caused by dynamic environmental conditions, technology-based systems capable of providing real-time information to the captain and bridge crew are required. These systems play an important role in improving the accuracy of situational perception, particularly during maneuvering operations in confined areas such as ports or docking facilities.
1) Installation of current meters and tide gauges in port areas or integrated into the vessel system. (C1)
2) Integration of environmental data (currents, wind, and tides) into navigation systems such as ECDIS or bridge display systems. (C2)
3) Implementation of alarms or warning thresholds when environmental conditions exceed safe operational limits. (C3)

These control measures aim to minimize perception failures and reduce the occurrence of unexpected and unanticipated current conditions. Weaknesses in planning and decision-making are among the major contributors to collision accidents. Therefore, clear and measurable operational standards are required prior to docking maneuvers. The following measures can be implemented:
1) Development of an environmental condition checklist prior to maneuvering, including weather, currents, tides, and visibility conditions. (C4)
2) Establishment of operational limits (operational envelope), such as maximum allowable wind speed and current conditions for docking operations. (C5)
3) Application of dynamic risk assessment prior to maneuvering to determine risk levels and appropriate mitigation measures. (C6)
4) Establishment of abort criteria to terminate

maneuvering operations when conditions are no longer considered safe. (C7)

These measures aim to improve the quality of decision-making and reduce dependence on individual intuition. Collision accidents are often triggered by a lack of effective coordination and communication among crew members, particularly under high-pressure conditions during maneuvering operations. The following measures can be implemented:

1) Mandatory berthing briefings prior to maneuvering to explain operational conditions, potential risks, and task distribution. (C8)
2) Implementation of closed-loop communication to ensure that every instruction is correctly understood and acknowledged. (C9)
3) Clarification of the roles and responsibilities of each bridge personnel member during maneuvering operations. (C10)

These control measures aim to reduce communication errors and improve coordination and synchronization of actions during operations. Low awareness of surrounding environmental conditions, including small objects such as fenders and changes in tidal conditions, has become one of the recurring causes of collision accidents. The following measures can be implemented:

1) Situational awareness training specifically focused on close-quarter maneuvering operations. (C11)
2) Scenario-based simulations or simulator training related to strong currents and adverse weather conditions. (C12)
3) Educational programs regarding the interpretation of tidal and sea current conditions. (C13)
4) Enhancement of visual awareness toward critical areas surrounding the vessel. (C14)

These measures aim to improve crew perception, situational awareness, and decision-making capabilities under dynamic operating conditions. A strong safety management system is required to ensure that all procedures are implemented consistently and sustainably. The following measures can be applied:

1) Standardization of berthing procedures within the company's Safety Management System (SMS). (C15)
2) Improvement of the near-miss reporting system, including minor incidents such as contact with fenders. (C16)
3) Documentation and dissemination of lessons learned from every incident. (C17)
4) Periodic evaluation of operational procedures based on incident data and field conditions. (C18)

These control measures aim to establish an adaptive and learning-based safety management system.

The adoption of technology is one of the most effective approaches to mitigating accidents caused by human factors. Several technological enhancements and strengthened collaboration with external stakeholders that can contribute to reducing maritime accidents include:

1) Installation of an AIS-based collision warning system to detect nearby vessels and provide early collision alerts. (C19)
2) Integration with the Vessel Traffic Service (VTS) during maneuvering and berthing operations in high-risk areas. (C20)

These Risk Control Options (RCOs) are intended to reduce the likelihood of collision accidents, particularly during berthing and maneuvering operations, by improving situational awareness and strengthening coordination between the vessel and shore-based traffic management authorities.

H. Analytical Hierarchy Process on Ship Sinking

After the Risk Control Options (RCOs) had been identified and described, an Analytic Hierarchy Process (AHP) assessment was conducted for these options. This process was carried out by assigning weights to the importance level of the criteria associated with the Risk Control Options for the ship sinking accident category. The assessment considered four main criteria, namely:

1) The cost required to implement the proposed Risk Control Option. (K1)
2) The applicability of the Risk Control Option to the existing conditions and organisational culture within the company. (K2)
3) The effectiveness level of the Risk Control Option in reducing the frequency of accident occurrence. (K3)
4) The effectiveness level of the Risk Control Option in reducing the consequences or impacts when an accident occurs. (K4)

As explained in the methodology section, the assessment was conducted using questionnaires completed by individuals who possess a strong understanding of the company's operations and decision-making processes. This approach was intended to gather expert judgement from personnel who are more familiar with the operational environment and have greater practical experience, thereby improving the effectiveness and relevance of the study. The questionnaire results are presented in Table 11.

As presented in Table 11, the calculation process began by converting the questionnaire assessment results into a normalized form. The normalized form refers to a condition where the total relationship values in each column equal one. Subsequently, the normalized values in each row were summed to obtain the priority value. These priority values were then used as the weighting factors for each criterion in the subsequent RCO assessment stage.

Based on the table, the resulting weight values for each criterion were as follows: cost (K1) = 0.06583, applicability (K2) = 0.2656, frequency effectiveness (K3) = 0.32879, and consequence effectiveness (K4) = 0.33978. In general, the AHP assessment indicates that, for the ship sinking case, the selected RCOs prioritize high consequence effectiveness and high frequency effectiveness over cost and applicability.

TABLE 11.
ANALYTICAL HIERARCHY PROCESS (AHP) SINKING CASE

	Quitionare				Normalized				Priority Value
	K1	K2	K3	K4	K1	K2	K3	K4	
C1	1.00	0.42	0.14	0.13	0.05495	0.12195	0.04545	0.04098	0.06583
C2	2.40	1.00	1.00	1.00	0.13187	0.29268	0.31818	0.31967	0.26560
C3	7.00	1.00	1.00	1.00	0.38462	0.29268	0.31818	0.31967	0.32879
C4	7.80	1.00	1.00	1.00	0.42857	0.29268	0.31818	0.31967	0.33978
SUM	18.20	3.42	3.14	3.13	1.00	1.00	1.00	1.00	1.00
								λ_{MAX} :	4.20187
								Consistency Index (CI) :	0.06729
								Consistency Ratio (CR) :	7.48%

In addition, to determine whether the assessment results satisfied the criteria required by the Analytic Hierarchy Process method, the consistency ratio of the evaluation was calculated. The resulting consistency ratio was 7.48%, which remains below the maximum acceptable threshold of 10%. This indicates that the assessment responses were consistent across all criteria. Therefore, the resulting weighting values can be considered valid and applicable for further analysis.

I. Analytical Hierarchy Process on Ship Collision

Following the assessment conducted for the ship sinking accident category, the Analytic Hierarchy Process (AHP) was also applied to the accident type with the highest number of occurrences, namely ship collisions. Similar to the previous analysis, the data were obtained using the same questionnaire, but with evaluations specifically focused on collision accidents.

As presented in Table 12, the questionnaire results were first converted into normalized values. These normalized values were then summed to obtain the priority values or weighting factors for each criterion related to ship collision accidents. Based on Table 12, the resulting priority values were as follows: cost (K1) = 0.04306, applicability (K2) = 0.27333, frequency effectiveness (K3) = 0.45532, and consequence effectiveness (K4) = 0.22828. These results indicate that, in the case of ship collisions, the most influential criteria in selecting the appropriate RCOs are applicability and frequency effectiveness.

TABLE 12.
ANALYTICAL HIERARCHY PROCESS (AHP) COLLISION CASE

	Quitionare				Normalized				Priority Value
	K1	K2	K3	K4	K1	K2	K3	K4	
C1	1.00	0.14	0.13	0.16	0.04425	0.03618	0.05932	0.03251	0.04306
C2	7.40	1.00	0.63	1.00	0.32743	0.26773	0.29661	0.20156	0.27333
C3	8.00	1.60	1.00	2.80	0.35398	0.42836	0.47458	0.56437	0.45532
C4	6.20	1.00	0.36	1.00	0.27434	0.26773	0.16949	0.20156	0.22828
SUM	22.60	3.74	2.11	4.96	1.00	1.00	1.00	1.00	1.00
								λ_{MAX} :	4.08619
								Consistency Index (CI) :	0.02873
								Consistency Ratio (CR) :	3.19%

Similar to the previous subsection, the consistency ratio (CR) was also calculated to e valuate the consistency of the assessment results. For the collision accident case, the resulting CR value was 3.19%. Since this value remains below the acceptable threshold of 10%, the resulting weighting values are considered consistent and valid for further analysis.

J. AHP Assessment Result on Ship Sinking RCOs

Using the weighting values for each criterion discussed in the previous subsection, the previously identified Risk Control Options (RCOs) were evaluated to determine the most optimal RCOs. Similar to the previous assessments, the evaluation of each RCO was conducted through questionnaires distributed to industry practitioners who possess strong familiarity with the operational environment and the company, thereby improving the effectiveness and relevance of the study.

The assessment was carried out based on the established criteria. Each RCO was evaluated in terms of Cost, Applicability, Frequency Effectiveness, and Consequence Effectiveness. The scores provided by each expert were then averaged and multiplied by the corresponding criterion weights to obtain the total score for each RCO. The results of this evaluation are presented in Table 13.

TABLE 13.
AHP ASSESSMENT RESULT OF SINKING CASE

	S1	S2	S3	S4	S5	**S6**	S7	**S8**	S9	S10	S11	S12	S13	S14	S15	**S16**	S17	S18	S19	S20
K1	0.20	0.24	0.16	0.28	0.30	**0.28**	0.26	**0.24**	0.18	0.20	0.28	0.26	0.24	0.24	0.25	**0.23**	0.26	0.24	0.22	0.25
K2	0.90	1.09	0.96	1.17	1.17	**1.14**	1.14	**1.12**	0.98	1.06	0.98	0.98	1.04	0.98	1.01	**1.09**	1.09	0.96	1.12	1.06
K3	1.28	1.05	1.45	1.45	1.32	**1.35**	1.28	**1.45**	1.41	1.32	1.18	1.28	1.28	1.35	1.38	**1.45**	1.35	1.38	1.45	1.28
K4	1.26	1.12	1.36	1.19	1.22	**1.39**	1.46	**1.36**	1.29	1.22	1.19	1.36	1.46	1.39	1.50	**1.39**	1.43	1.36	1.36	1.19
SUM	3.64	3.51	3.92	4.09	4.01	**4.16**	4.14	**4.16**	3.87	3.80	3.63	3.88	4.02	3.96	4.14	**4.16**	4.12	3.94	4.14	3.78

Table 13 presents the weighted evaluation results and indicates that the three highest-ranked RCOs are:

1) Development and implementation of a decision matrix as a guideline for decision-making under both normal and emergency conditions. (S6)
2) Development of ballasting procedures integrated into every stage of loading and unloading operations to maintain vessel stability. (S8)
3) Periodic updates of risk assessments (HIRADC/JSA) based on incidents, near-miss events, and lessons learned. (S16)

K. AHP Assessment Result on Ship Collision RCOs

The same approach was applied to the Risk Control Options (RCOs) for collision accident cases. The assessment was conducted using the same group of experts, who evaluated each RCO based on the predetermined criteria, namely cost, applicability, frequency effectiveness, and consequence effectiveness.

The assessment results were then multiplied by the corresponding weighting values obtained from the previous AHP analysis, resulting in three RCOs with the highest overall scores, namely

1) Situational awareness training specifically focused on close-quarter maneuvering operations. (C11)
2) Enhancement of visual awareness toward critical areas surrounding the vessel. (C14)
3) Improvement of the near-miss reporting system, including minor incidents such as contact with fenders. (C16)

The calculation results for each RCO based on the weighting values determined through the AHP method are presented in Table 14.

TABLE 14.
AHP ASSESSMENT RESULT OF COLLISION CASE

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	**C11**	C12	C13	**C14**	C15	**C16**	C17	C18	C19	C20
K1	0.10	0.09	0.09	0.17	0.18	0.16	0.17	0.19	0.19	0.18	**0.16**	0.16	0.16	**0.18**	0.15	**0.16**	0.16	0.16	0.16	0.16
K2	0.93	0.93	0.96	1.12	1.07	1.12	1.09	1.18	1.18	1.20	**1.15**	1.07	1.15	**1.18**	1.09	**1.23**	1.18	1.20	1.15	0.98
K3	1.78	1.87	1.82	1.96	1.96	1.91	2.00	2.00	1.87	1.96	**2.09**	1.91	1.96	**2.05**	2.00	**2.00**	1.87	1.96	2.05	1.87
K4	0.84	0.91	0.82	0.89	0.94	0.91	1.00	0.96	0.84	0.89	**0.98**	1.03	0.91	**0.96**	1.00	**1.03**	0.96	0.98	0.94	0.98
SUM	3.65	3.80	3.69	4.14	4.14	4.11	4.27	4.32	4.08	4.23	**4.39**	4.16	4.18	**4.36**	4.25	**4.42**	4.16	4.30	4.30	4.00

L. CBA Assessment Result on Ship Sinking RCOs

After the calculations using AHP were completed, each RCO was further assessed using the Formal Safety Assessment (FSA) method through Cost Benefit Assessment (CBA). As discussed in Chapter II, this calculation uses the Benefit Cost Ratio (BCR), which is presented in Equation (4). The BCR calculation results are shown in Table 15. In Table 15, the Initial Total Cost was obtained from the total repair cost of ship sinking accidents, amounting to IDR 13,200,000,000, with an accident frequency of one occurrence.

TABLE 15.
CBA ASSESSMENT RESULT OF SINKING CASE

RCO	Initial Total Cost	Frequency Effectiveness	Final Frequency	Consequence Effectiveness	Repair Cost Each	Implementation Cost	Benefit	BCR
S1	IDR 13.2 B	3.9	0.720	3.7	IDR 9.977 B	IDR 2,060 M	IDR 6.017 B	2.921
S2	IDR 13.2 B	3.2	0.770	3.3	IDR 10.325 B	IDR 2,640 M	IDR 5.247 B	1.988
S3	IDR 13.2 B	4.4	0.684	4	IDR 9.715 B	IDR 4,080 M	IDR 6.554 B	1.606
S4	**IDR 13.2 B**	**4.4**	**0.684**	**3.5**	**IDR 10.151 B**	**IDR 576 M**	**IDR 6.256 B**	**10.861**
S5	IDR 13.2 B	4	0.713	3.6	IDR 10.064 B	IDR 672 M	IDR 6.026 B	8.968
S6	IDR 13.2 B	4.1	0.706	4.1	IDR 9.628 B	IDR 744 M	IDR 6.406 B	8.610
S7	IDR 13.2 B	3.9	0.720	4.3	IDR 9.454 B	IDR 696 M	IDR 6.393 B	9.186
S8	IDR 13.2 B	4.4	0.684	4	IDR 9.715 B	IDR 888 M	IDR 6.554 B	7.380
S9	IDR 13.2 B	4.3	0.691	3.8	IDR 9.889 B	IDR 2,400 M	IDR 6.364 B	2.652
S10	IDR 13.2 B	4	0.713	3.6	IDR 10.064 B	IDR 1,392 M	IDR 6.026 B	4.329
S11	**IDR 13.2 B**	**3.6**	**0.742**	**3.5**	**IDR 10.151 B**	**IDR 528 M**	**IDR 5.673 B**	**10.744**
S12	IDR 13.2 B	3.9	0.720	4	IDR 9.715 B	IDR 624 M	IDR 6.205 B	9.944
S13	IDR 13.2 B	3.9	0.720	4.3	IDR 9.454 B	IDR 1,464 M	IDR 6.393 B	4.367
S14	IDR 13.2 B	4.1	0.706	4.1	IDR 9.628 B	IDR 1,008 M	IDR 6.406 B	6.355
S15	IDR 13.2 B	4.2	0.698	4.4	IDR 9.367 B	IDR 1,368 M	IDR 6.658 B	4.867
S16	IDR 13.2 B	4.4	0.684	4.1	IDR 9.628 B	IDR 840 M	IDR 6.613 B	7.873
S17	**IDR 13.2 B**	**4.1**	**0.706**	**4.2**	**IDR 9.541 B**	**IDR 648 M**	**IDR 6.468 B**	**9.981**
S18	IDR 13.2 B	4.2	0.698	4	IDR 9.715 B	IDR 816 M	IDR 6.414 B	7.861
S19	IDR 13.2 B	4.4	0.684	4	IDR 9.715 B	IDR 740 M	IDR 6.554 B	8.856
S20	IDR 13.2 B	3.9	0.720	3.5	IDR 10.151 B	IDR 825 M	IDR 5.891 B	7.141

In the Cost–Benefit Analysis (CBA), questionnaires were distributed to obtain expert judgment regarding the effectiveness of each Risk Control Option (RCO). The experts assessed the effectiveness on a five-point scale, where a score of **5** represents the maximum level of risk reduction.

Based on the questionnaire results for ship sinking accidents, the average expert assessment indicated that, under the maximum effectiveness level (score of 5), the frequency of ship sinking accidents could be reduced to **one occurrence every 7.8 years**, which is equivalent to a frequency of **0.641 occurrences over a five-year period**. The reduction in accident frequency was assumed to be proportional to the effectiveness score. For example, an effectiveness score of **3.9** corresponds to a reduced frequency of **0.72 occurrences over five years**. The effectiveness scores were derived from the expert judgments obtained through the distributed questionnaires.

TABLE 16.
CBA ASSESSMENT RESULT OF COLLISION CASE

RCO	Initial Total Cost	Frequency Effectiveness	Final Frequency	Consequence Effectiveness	Repair Cost Each	Implementation Cost	Benefit	BCR
C1	IDR 5.40 B	3.9	24	3.7	IDR 103.57 M	IDR 2,288 M	IDR 2,914 M	1.274
C2	IDR 5.40 B	4.1	23	4	IDR 102.24 M	IDR 2,880 M	IDR 3,048 M	1.059
C3	IDR 5.40 B	4	23	3.6	IDR 104.02 M	IDR 1,350 M	IDR 3,008 M	2.228
C4	**IDR 5.40 B**	**4.3**	**22**	**3.9**	**IDR 102.68 M**	**IDR 528 M**	**IDR 3,141 M**	**5.949**
C5	IDR 5.40 B	4.3	22	4.1	IDR 101.8 M	IDR 672 M	IDR 3,160 M	4.703
C6	IDR 5.40 B	4.2	22	4	IDR 102.24 M	IDR 840 M	IDR 3,151 M	3.751
C7	IDR 5.40 B	4.4	21	4.4	IDR 100.46 M	IDR 576 M	IDR 3,290 M	5.712
C8	**IDR 5.40 B**	**4.4**	**21**	**4.2**	**IDR 101.35 M**	**IDR 552 M**	**IDR 3,272 M**	**5.927**
C9	IDR 5.40 B	4.1	23	3.7	IDR 103.57 M	IDR 670 M	IDR 3,018 M	4.504
C10	IDR 5.40 B	4.3	22	3.9	IDR 102.68 M	IDR 576 M	IDR 3,141 M	5.453
C11	IDR 5.40 B	4.6	20	4.3	IDR 100.91 M	IDR 1,200 M	IDR 3,382 M	2.818
C12	IDR 5.40 B	4.2	22	4.5	IDR 100.02 M	IDR 1,776 M	IDR 3,200 M	1.802
C13	IDR 5.40 B	4.3	22	4	IDR 102.24 M	IDR 720 M	IDR 3,151 M	4.376
C14	**IDR 5.40 B**	**4.5**	**21**	**4.2**	**IDR 101.35 M**	**IDR 460 M**	**IDR 3,272 M**	**7.112**
C15	IDR 5.40 B	4.4	21	4.4	IDR 100.46 M	IDR 840 M	IDR 3,290 M	3.917
C16	IDR 5.40 B	4.4	21	4.5	IDR 100.02 M	IDR 744 M	IDR 3,300 M	4.435
C17	IDR 5.40 B	4.1	23	4.2	IDR 101.35 M	IDR 650 M	IDR 3,069 M	4.721
C18	IDR 5.40 B	4.3	22	4.3	IDR 100.91 M	IDR 768 M	IDR 3,180 M	4.141
C19	IDR 5.40 B	4.5	21	4.1	IDR 101.8 M	IDR 950 M	IDR 3,262 M	3.434
C20	IDR 5.40 B	4.1	23	4.3	IDR 100.91 M	IDR 868 M	IDR 3,079 M	3.547

In addition to accident frequency, the reduction in accident consequences was also evaluated based on the experts' assessments. According to the average questionnaire results, the implementation of an RCO with the maximum effectiveness level (score of **5**) is expected to reduce the accident consequences by **33%**.

A similar approach was applied to the consequence impact. For effectiveness values below 5, the reduction decreases proportionally according to its ratio to the maximum effectiveness value, similar to the frequency effectiveness calculation. Therefore, Table 15 shows that the repair cost per accident decreases according to the effectiveness level of each RCO.

Implementation Cost represents the expenses required to realize each RCO. These costs include purchasing, training, maintenance, and commissioning expenses over a 5-year period. The values were obtained by estimating the required costs for each RCO. Meanwhile, Benefit represents the gain calculated from the difference between the initial total cost and the final total cost. The final total cost itse lf is obtained by multiplying the final frequency (after the RCO implementation) by the Final Repair Cost for each case. Based on these calculations, the BCR value for each RCO was obtained. From these results, the three best RCOs according to the CBA assessment are

1) Implementation of a loading sequence checklist that must be used and verified at every stage of the operation. (S4)
2) Implementation of mandatory checklist-based briefings for all truck drivers before entering the vessel. (S11)
3) Documentation and dissemination of lessons learned to all relevant personnel. (S17)

M. CBA Assessment Result on Ship Collision RCOs

The expected reduction in the frequency of collision accidents after the implementation of the Risk Control Options (RCOs) at PT. X was evaluated using the same approach as that applied to ship sinking accidents, namely expert judgment. Based on the average assessment from the experts, the expected frequency of collision accidents is projected to decrease from 45 incidents during the 2020–2024 period (five years) to 18 incidents over the same five-year period. In other words, assuming the RCOs are implemented with perfect effectiveness, the number of collision accidents is expected to be reduced by 27 incidents, resulting in a total of 18 collision cases within five years.

Regarding the reduction in accident consequences, the experts estimated that the implementation of an effective RCO would reduce the impact of each collision accident by 18%. The consequence reduction was assessed using the same approach as described previously, based on the average repair cost incurred for each accident. The average repair cost for a collision accident was estimated at IDR 120,000,000 per incident. Therefore, the expected repair cost after the implementation of the RCO is projected to decrease to approximately IDR 97,800,000 per accident. The results of the cost reduction and the Benefit Cost Ratio calculations are presented in Table 17.

From CBA Assessment, the three best RCOs is obtained as follow:

1) Development of an environmental condition checklist prior to maneuvering, including weather, currents, tides, and visibility conditions. (C4)
2) Mandatory berthing briefings prior to maneuvering to explain operational conditions, potential risks, and task distribution. (C8)
3) Enhancement of visual awareness toward critical areas surrounding the vessel. (C14)

TABLE 17.
CBA-AHP ASSESSMENT RESULT

Sinking Case					Collision Case				
RCO	BCR	Converted BCR	AHP Score	Final Score	RCO	BCR	Converted BCR	AHP Score	Final Score
S1	2.921	1.779	3.640	2.710	C1	1.274	1.179	3.653	2.416
S2	1.988	1.401	3.506	2.453	C2	1.059	1.038	3.804	2.421
S3	1.606	1.246	3.920	2.583	C3	2.228	1.804	3.695	2.749
S4	**10.861**	**5.000**	**4.088**	**4.544**	**C4**	**5.949**	**4.239**	**4.141**	**4.190**
S5	8.968	4.232	4.010	4.121	C5	4.703	3.423	4.136	3.780
S6	8.610	4.087	4.160	4.123	C6	3.751	2.800	4.110	3.455
S7	9.186	4.320	4.142	4.231	C7	5.712	4.084	4.273	4.179
S8	7.380	3.588	4.165	3.877	**C8**	**5.927**	**4.224**	**4.323**	**4.273**
S9	2.652	1.670	3.872	2.771	C9	4.504	3.293	4.081	3.687
S10	4.329	2.351	3.798	3.074	C10	5.453	3.914	4.232	4.073
S11	**10.744**	**4.953**	**3.632**	**4.292**	C11	2.818	2.190	4.388	3.289
S12	9.944	4.628	3.881	4.254	C12	1.802	1.525	4.161	2.843
S13	4.367	2.366	4.023	3.194	C13	4.376	3.209	4.183	3.696
S14	6.355	3.172	3.961	3.567	**C14**	**7.112**	**5.000**	**4.364**	**4.682**
S15	4.867	2.569	4.135	3.352	C15	3.917	2.909	4.252	3.580
S16	7.873	3.788	4.159	3.974	C16	4.435	3.248	4.420	3.834
S17	**9.981**	**4.643**	**4.121**	**4.382**	C17	4.721	3.435	4.165	3.800
S18	7.861	3.783	3.940	3.861	C18	4.141	3.055	4.297	3.676
S19	8.856	4.187	4.139	4.163	C19	3.434	2.593	4.297	3.445
S20	7.141	3.491	3.784	3.638	C20	3.547	2.667	3.996	3.332

N. CBA-AHP Result on Ship Sinking

The CBA-AHP assessment was conducted using an equal weighting ratio of 50:50. As shown in Table 17, the benefit-cost ratio (BCR) values were first converted to align their range with the AHP scale range (1–5). The conversion was carried out by assigning the highest BCR value of the sinking ship scenario to a scale value of 5, while a BCR value of 1 was assigned to a scale value of 1. Subsequently, the intermediate values between these two points were determined through interpolation.

Afterward, the Final CBA-AHP Score for each RCO was obtained by combining 50% of the Converted CBA Score and 50% of the AHP Score. Based on the final scores, the best RCO is:

1) Implementation of a loading sequence checklist that must be used and verified at every stage of the operation. (S4)
2) Implementation of mandatory checklist-based briefings for all truck drivers before entering the vessel. (S11)
3) Documentation and dissemination of lessons learned to all relevant personnel. (S17)

The integration of the Analytic Hierarchy Process (AHP) and Cost–Benefit Analysis (CBA) demonstrates that the three selected Risk Control Options (RCOs) represent not only the most economically beneficial solution, but also a decision that considers multiple criteria, including cost, applicability, frequency effectiveness, and severity effectiveness. The results indicate that these RCOs provide an appropriate and effective solution for reducing ship sinking accidents. The implementation of all three RCOs is expected to reduce the accident frequency to 0.684 incidents over a five-year period, which is equivalent to approximately one accident every 7.31 years. In addition, the combined implementation of these RCOs is projected to reduce the average accident cost by 27.72% per accident.

O. CBA-AHP Result on Ship Collision

The CBA-AHP assessment was also conducted for the ship collision case using an equal weighting ratio of 50:50. As presented in Table 17, the benefit-cost ratio values were converted using the same conversion method described in the previous subsection. Based on the final scores, the best RCO for the ship collision accident case is:

1) Development of an environmental condition checklist prior to maneuvering, including weather, currents, tides, and visibility conditions. (C4)
2) Mandatory berthing briefings prior to maneuvering to explain operational conditions, potential risks, and task distribution. (C8)
3) Enhancement of visual awareness toward critical areas surrounding the vessel. (C14)

As discussed in the ship sinking case, the integration of Cost–Benefit Analysis (CBA) and the Analytic Hierarchy Process (AHP) in the collision accident case serves the same objective: to identify the most appropriate alternative solution based not only on economic benefits but also on a multi-criteria evaluation. By incorporating AHP, the assessment considers multiple decision criteria, including cost, applicability, frequency effectiveness, and severity effectiveness. For ship collision accidents, the implementation of the three selected Risk Control

Options (RCOs) is expected to reduce the accident frequency to 21 incidents over a five-year period while decreasing the average repair cost per accident by 15.54%.

IV. Conclusion

This study concludes that the integration of the Formal Safety Assessment (FSA) with the SHIELD taxonomy and the Analytic Hierarchy Process (AHP), combined with the Cost–Benefit Analysis (CBA-AHP) approach, provides a robust and systematic methodology for improving the safety of ferry passenger vessel operations. Historical accident data from PT. X identified ship sinking and ship collision as the dominant accident scenarios contributing to operational risk. By integrating hazard identification, human-factor analysis, multi-criteria decision-making, and economic evaluation, the proposed framework enables the selection of Risk Control Options (RCOs) that are both technically effective and economically feasible.

Using an equal weighting ratio of 50:50 between the AHP and CBA scores, the CBA-AHP assessment identified the three highest-priority RCOs for each accident scenario. For ship sinking, the selected RCOs are the implementation of a loading sequence checklist that must be used and verified at every stage of the operation, mandatory checklist-based briefings for all truck drivers before entering the vessel, and documentation and dissemination of lessons learned to all relevant personnel. The combined implementation of these measures is expected to reduce the accident frequency to 0.684 incidents over a five-year period, equivalent to approximately one accident every 7.31 years, while reducing the average accident cost by 27.72% per incident.

For ship collision accidents, the selected RCOs consist of the development of an environmental condition checklist prior to maneuvering, mandatory berthing briefings to communicate operational conditions, potential risks, and task distribution, and enhancement of visual awareness toward critical areas surrounding the vessel. The implementation of these three measures is projected to reduce the collision frequency to 21 incidents over a five-year period and decrease the average repair cost per accident by 15.54%.

Overall, the integration of AHP and CBA demonstrates that the selected RCOs are not solely based on economic benefits but also account for multiple decision criteria, including cost, applicability, frequency effectiveness, and severity effectiveness. Consequently, the proposed FSA–SHIELD–CBA-AHP framework provides a practical, quantitative, and evidence-based decision-support methodology for maritime safety management. The findings support the transition from reactive accident response toward proactive risk prevention and offer a replicable approach for enhancing safety performance in ferry operations and other maritime transportation systems.

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