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Risk Assessment Model of Ship Accidents Using Fault Tree Analysis (FTA) Based on Incident Categories and Fatality Factors

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***Abstract*−** Maritime transportation is essential for economic development and regional connectivity in Indonesia; however, fatal ship accidents remain a serious safety concern. This study aims to develop a severity-oriented risk assessment model by integrating accident categories and fatality factors using Fault Tree Analysis (FTA). A quantitative approach is applied to secondary data from 50 documented fatal ship accidents in Indonesian waters between 2017 and 2022, involving 295 fatalities. FTA is used to construct causal relationships between basic events, intermediate accident categories, and the top event of fatal ship accidents through qualitative identification of dominant pathways and quantitative estimation of probability contributions. The results indicate that sinking and fire are the most critical accident categories, accounting for more than three-quarters of total fatalities. Human-related factors, particularly insufficient access to life-saving appliances and ineffective emergency response, are the dominant contributors, followed by technical factors such as fire system failure and toxic gas exposure. Environmental and external factors mainly amplify the severity of accidents by reducing survivability. This study concludes that fatal ship accidents are driven primarily by dominant high-impact causal events rather than complex combinations of low-probability failures.

Keywords− Fault Tree Analysis; Ship accidents; Fatality risk; Maritime safety.

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I. INTRODUCTION

Maritime transport serves as a cornerstone of transportation and trade systems in coastal and island nations, where it underpins economic activity, supply chain movement, and interregional access. The substantial increase in shipping traffic over recent years has led to a corresponding rise in the likelihood of marine accidents, particularly in confined waters, coastal corridors, and heavily trafficked shipping routes characterized by complex navigation conditions. International safety records reveal that incidents involving vessel collisions and groundings represent a significant share of major maritime accidents, exceeding one-fifth of total reported cases and highlighting their prominent role in shaping global maritime risk patterns [1], [2]. Empirical investigations in maritime safety consistently indicate that most severe marine incidents are strongly associated with human-centered causes, such as insufficient competency development, flawed operational judgments, and breakdowns in communication processes, with their contribution estimated to account for approximately 60 to 80 percent of major accidents across different vessel categories and operating environments [3], [4]. Studies addressing accident types with severe consequences, including vessel collisions as well as fire and explosion events, demonstrate that accident seriousness and the likelihood of fatalities rise markedly when human mistakes, equipment malfunctions, and adverse environmental conditions occur simultaneously, especially in densely trafficked and restricted maritime areas [5], [6].

Evidence from maritime accident investigations in Indonesia shows that vessel collisions have remained among the most frequent and serious types of marine incidents over the last twenty years. Official national investigation records report no fewer than 22 collision cases examined between 2003 and 2023, indicating that such events constitute an ongoing safety challenge rather than isolated occurrences in Indonesian waters [7]. These collision events often trigger subsequent accidents, including ship sinking, fires, or explosions, which substantially intensify their impacts in terms of human casualties, environmental harm, and financial losses. Data on fatalities from maritime accidents during the period 2017–2022 reveal 50 major incidents resulting in 295 deaths, with collision-related accidents commonly serving as the initiating events that develop into sinking and fire scenarios where fatality levels are considerably higher than in accidents not involving collisions [8]. Moreover, spatial analysis of accident distribution highlights a close relationship between collision occurrences and areas characterized by dense vessel traffic, restricted and congested navigation routes, port entrance zones, and locations lacking adequate navigational aids and traffic control systems, underscoring structural weaknesses within national maritime transport corridors [7], [9].

Findings from maritime accident investigations consistently reveal that ship collisions are not triggered by a single cause but emerge from the combined influence of human, technical, and environmental elements interacting

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within the maritime operational system. Research based on accident reports and probabilistic risk assessment approaches shows that human-centered issues including inadequate training, insufficient operational experience, fatigue, reduced situational awareness, flawed navigational decisions, and non-compliance with the International Regulations for Preventing Collisions at Sea constitute the most influential contributors to collision incidents across various vessel categories and operational settings [3], [4], [10]. Technical aspects such as engine and propulsion malfunctions, deficiencies in navigational instruments, and failures in onboard communication systems further intensify collision likelihood, particularly when they coincide with human mistakes during critical navigation stages [11], [12]. Environmental and external factors also significantly affect collision probability, as incidents occur more frequently in restricted and crowded waterways, regions with strong currents, unfavorable weather, and limited access to support services such as tug assistance and vessel traffic management, which collectively increase navigational workload and constrain operational safety margins [7], [8]. Although collision events arise from multiple interacting causes, both international and domestic studies consistently identify human factors as the dominant source of collision risk, accounting for most causal pathways in fault tree and Bayesian network analyses and highlighting the importance of structured, human-focused risk control measures in maritime safety management [13], [14].

Although many ship accidents do not lead to loss of life, empirical findings indicate that the probability of fatalities rises sharply when several unfavorable conditions occur at the same time during and after an incident. Research on accident outcomes shows that deaths are considerably more likely when human mistakes occur together with technical malfunctions, such as engine failure, defects in navigation systems, or breakdowns in communication, because these combinations severely limit the crew's ability to manage the situation and prevent further escalation [15], [16]. Ineffective or delayed emergency actions and failure to follow established safety and evacuation protocols further increase the likelihood of fatal consequences, especially in collision events that quickly develop into sinking or fire scenarios where rapid and accurate decisions are essential [17], [18]. Environmental pressures, including strong currents, harsh weather, and restricted waterways, have also been proven to reduce survival chances after collisions by complicating rescue efforts and accelerating vessel instability [19], [20]. As a result, fatalities are now widely regarded in maritime risk studies as a primary measure of accident severity rather than merely a consequence of accident frequency, since they capture the combined impact of human, technical, and environmental breakdowns and offer a more relevant basis for assessing and prioritizing safety improvement strategies [21], [22].

Traditional approaches to maritime accident risk assessment are still largely descriptive and fragmented, as many studies concentrate on individual elements such as human error, equipment malfunction, or environmental conditions without systematically examining the causal relationships among them. This limitation reduces their capability to explain how relatively minor initiating events can interact and develop into severe accidents involving fatalities. Evaluations of existing maritime risk assessment practices indicate that methods based solely on single factors or accident frequency fail to adequately represent the complex mechanisms through which accidents propagate, and therefore offer limited guidance for preventive decision making in high-risk maritime operations [2], [21]. To address these shortcomings, Fault Tree Analysis (FTA) has gained recognition as a structured and reliable risk analysis technique that explicitly models the logical connections between basic causes, intermediate failures, and top events such as ship collisions, sinking, or fire [23], [24]. By identifying minimal cut sets, FTA makes it possible to determine the most critical combinations of human, technical, and environmental contributors that are likely to lead to fatal outcomes, supporting both qualitative insight and quantitative probability evaluation of high-impact scenarios [8]. Consequently, incorporating accident categories and fatality-related factors into an FTA-based framework provides a more integrated approach to maritime risk assessment, capturing accident severity not only through likelihood of occurrence but also through potential loss of life, which is essential for effective safety management and policy development.

Although maritime safety research has expanded considerably, substantial deficiencies remain in the formulation of ship accident risk assessment models, particularly regarding the direct linkage between accident categories and fatality-related outcomes. Most existing investigations concentrate on accident probability, system reliability, or human error contributions, while positioning fatalities merely as indirect consequences rather than as primary indicators of risk, thereby reducing their relevance for life-safety-focused decision making. In addition, only a small number of studies employ national accident investigation databases to develop Fault Tree Analysis (FTA) models that account for country-specific operational conditions, traffic density, and regulatory environments [25], [26]. This limitation is especially pronounced in the Indonesian maritime sector, where accident causation patterns differ from those observed in open seas or regions with advanced traffic management systems. Bridging this gap requires an analytical framework capable of supporting preventive and evidence-based risk management by systematically representing the interactions between incident types and fatality-driving factors within a single causal structure. Therefore, this study aims to construct a ship accident risk assessment model using Fault Tree Analysis that integrates incident categories with fatality determinants in order to identify the dominant contributors to fatal outcomes, establish a scientific basis for targeted risk mitigation measures, and support maritime safety policies focused on reducing loss of life in sea transportation systems.

Ship accidents remain a critical maritime safety issue because most existing risk assessment studies primarily focus on accident occurrence probability, technical reliability, or human error as separate factors, while fatalities are often treated merely as secondary outcomes rather than as core indicators of accident severity. This limitation restricts the ability to understand how interactions between accident incident categories and fatality-related factors escalate into deadly events. The novelty of this study lies in the development of a ship accident risk assessment model based on Fault Tree Analysis (FTA) that explicitly integrates accident incident categories with fatality factors within a unified causal framework, enabling accident severity to be evaluated not only by frequency but also by its fatal consequences. Accordingly, the objective of this research is to model the causal relationships among human, technical, and environmental factors contributing to fatal ship accidents, to identify critical combinations of contributing factors or minimal cut sets that significantly increase the risk of loss of life, and to provide a robust analytical foundation for preventive decision making, targeted risk mitigation strategies, and maritime safety policies oriented toward the protection of human life in maritime transportation systems

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Figure 1. FTA Research Procedure

II. METHOD

A. *Research Design and Approach*

This study employs a quantitative research design based on a causal risk assessment approach to systematically examine ship accident phenomena using empirical accident and fatality data obtained from the uploaded dataset. The research is conducted as an analytical and explanatory investigation aimed at identifying and modeling cause–effect relationships leading to fatal ship accidents, rather than merely describing accident frequencies. Fault Tree Analysis (FTA) is adopted as the primary methodological framework to deconstruct complex accident scenarios into structured causal pathways, allowing for the identification of basic events, intermediate events, and their logical interrelationships that ultimately result in fatal outcomes. The analysis specifically focuses on ship accidents classified by incident type, including collision, sinking, fire, and explosion, and incorporates fatality-related factors as the principal risk indicator to represent accident severity. By grounding the FTA model in actual accident and fatality records contained in the uploaded dataset, this study ensures that the resulting risk assessment reflects real operational conditions and supports an evidence-based evaluation of critical failure combinations that contribute to loss of life in maritime transportation.

B. *Research Procedure*

The research procedure illustrated in the figure represents a structured and sequential application of Fault Tree Analysis (FTA) for ship accident investigation based on empirical accident reports. The process begins with the collection of collision accident investigation reports, which are then systematically reviewed to evaluate their relevance, completeness, and suitability for further analysis. This screening ensures that only high-quality and informative cases are selected for subsequent stages, while reports that do not meet the selection criteria are excluded from the analytical process. The selected reports are used to develop a comprehensive system description and conduct hazard identification, in which the operational context, accident scenarios, and potential hazards are defined based on factual investigation data. These cases then serve as the basis for constructing the fault tree model, which logically represents how basic events and intermediate failures propagate toward the top event, defined as a ship accident with fatal consequences. The analysis proceeds along two complementary pathways: a qualitative analysis to identify minimal cut sets representing the simplest and most critical combinations of failures, and a quantitative analysis to estimate the probabilities of failure events using historical accident data. The results from both approaches are integrated in the importance evaluation stage, where contributing factors are ranked according to their relative significance and influence on accident severity. This process culminates in a results analysis phase in which the findings are synthesized to support conclusions and provide risk-based recommendations.

C. *Research Instruments, Data Sources, and Data Analysis Techniques*

The research instruments used in this study consist of structured accident report extraction forms and analytical templates designed to systematically capture relevant information from official maritime accident investigation records. The research data comprise secondary data obtained from 50 collision accident investigation reports issued by the Republic of Indonesia National Transportation Safety Committee (NTSC) for the period 2017–2022. These reports provide detailed factual information, including vessel characteristics, voyage routes, time and location of the accidents, accident scenarios, sequences of events, and associated operational and environmental conditions. The collected data are first organized to develop a comprehensive general description of each accident, which serves as the empirical basis for identifying main events and contributing factors related to human, technical, and environmental causes. Data analysis is performed using Fault Tree Analysis (FTA) through two complementary stages. The qualitative analysis focuses on constructing the fault tree structure and identifying minimal cut sets that represent the simplest and most critical combinations of basic events leading to collision accidents with fatal outcomes. Subsequently, the quantitative analysis estimates the probability of each basic event and its contribution to the top event by utilizing historical frequency data derived from the investigated reports. Through this integrated analytical process, the study evaluates both causal relationships and risk magnitude, thereby providing a systematic assessment of the dominant factors contributing to fatal ship collision accidents.

III. Results and Discussion

A. *Overview of Ship Accident and Fatality Data in Indonesia (2017–2022)*

This section provides an overview of ship accident and fatality data in Indonesia based on officially documented maritime accident investigation reports covering the period from 2017 to 2022. The dataset consists of 50 ship accident cases involving various vessel types, including passenger ships, Ro-Ro vessels, tankers, bulk carriers, general cargo ships, and fishing vessels operating in diverse maritime environments. The accidents are classified into major incident categories such as collision, sinking, fire, grounding, and other operational incidents, with particular emphasis on fatality outcomes. Fatality data are employed as a primary indicator of accident severity, reflecting not only the occurrence of accidents but also their human consequences. This overview establishes a descriptive foundation for understanding temporal trends, accident categories, vessel characteristics, and dominant causes of death, which together provide the empirical basis for subsequent causal modeling and risk assessment using Fault Tree Analysis.

TABLE 1.
SHIP ACCIDENT AND FATALITY DATA IN INDONESIA (2017–2022)

No	Date	Time	Vessel Name	Vessel Type	Class	Accident Category	Fatalities	Cause of Death
1	Jan 1, 2017	08:30	KM Zahro Express	Passenger	Non-Class	Fire	24	Gas poisoning
2	April 19, 2017	09:00	LCT Rimba Raya XXXI	Landing Craft	Non-Class	Fire	1	Explosion pressure
3	April 21, 2017	16:15	MT Layar Samudera	Tanker	BKI	Fire	3	Burn injuries
4	May 20, 2017	16:00	KM Mutiara Sentosa I	Ro-Ro Passenger	BKI	Fire	5	Falling
5	June 14, 2017	02:30	KM Avatar	Container	BKI	Sinking	1	Delayed rescue
6	July 25, 2017	09:40	SB Rejeki Baru Kharisma	Passenger	Non-Class	Sinking	10	Evacuation obstruction
7	Sep 13, 2017	00:38	MT Kartika Segara; JBB De Rong 19	Tanker; Dredger	NK; SL	Collision	5	Delayed rescue
8	Dec 18, 2017	16:45	KM Mutiara Ferindo I	Ro-Ro Passenger	BKI	Other	1	Crushed by cargo
9	Nov 10, 2017	07:55	TB Surya Wira 21	Tug Boat	NK	Other	1	Crushed by cargo
10	Jan 1, 2018	08:10	Anugrah Express	Passenger	Non-Class	Sinking	8	Evacuation obstruction
11	Jan 3, 2018	17:30	Awet Muda	Passenger	Non-Class	Sinking	13	Lack of flotation access
12	Jan 21, 2018	23:40	Mariner	Bulk Carrier	NK	Other	1	Falling
13	Jan 21, 2018	18:00	Itanini	General Cargo	BKI	Sinking	2	Lack of flotation access
14	Jan 27, 2018	17:00	Pinang Jaya	General Cargo	BKI	Sinking	1	Delayed rescue
15	Feb 20, 2018	04:45	Kayong Utara	Ro-Ro Passenger	BKI	Grounding	1	Evacuation obstruction
16	Feb 24, 2018	20:00	Sumiei	General Cargo	BKI	Other	5	Gas poisoning
17	March 31, 2018	22:02	Ever Judger	Bulk Carrier	DNV	Other	5	Burn injuries
18	April 26, 2018	05:22	STB 1500	Bulk Carrier	BKI	Sinking	1	Suffocation

CONTINUED TABLE 1.
SHIP ACCIDENT AND FATALITY DATA IN INDONESIA (2017–2022)

No	Date	Time	Vessel Name	Vessel Type	Class	Accident Category	Fatalities	Cause of Death
19	May 22, 2018	14:05	Harapan Baru	Passenger	Non-Class	Grounding	5	Evacuation obstruction
20	June 2, 2018	15:12	Bull Flores	Tanker	RI	Other	2	Crushed by cargo
21	June 13, 2018	12:45	Arista	Fishing Vessel	Non-Class	Sinking	17	Lack of flotation access
22	June 18, 2018	17:10	Sinar Bangun 4	Passenger	Non-Class	Sinking	3	Delayed rescue
23	July 3, 2018	13:40	Lestari Maju	Ro-Ro Passenger	BKI	Grounding	34	Unable to swim
24	July 18, 2018	13:30	Penta Prima	Fishing Vessel	Non-Class	Sinking	2	Suffocation
25	July 20, 2018	21:45	Bunga Melati 79; Golden Way 3310	Cargo; Barge	BKI	Collision	1	Lack of flotation access
26	August 4, 2018	05:35	Satya Kencana IX	Ro-Ro Passenger	BKI	Fire	1	Evacuation obstruction
27	August 15, 2018	11:00	Bandeng	Ro-Ro Passenger	BKI	Sinking	3	Lack of flotation access
28	Sep 14, 2018	11:40	Fungka Permata V	Passenger	Non-Class	Fire	13	Lack of flotation access
29	Dec 2, 2018	02:15	Gerbang Samudra I	Ro-Ro Passenger	BKI	Fire	3	Burn injuries
30	Jan 14, 2019	04:30	Victoria 11	Tanker	BKI	Other	1	Gas poisoning
31	April 6, 2019	15:50	Bistari 8	General Cargo	BKI	Other	2	Crushed by cargo
32	April 22, 2019	16:32	Virgo 18; Windu Karsa Dwitya	Ro-Ro Passenger	BKI	Collision	1	Crushed by cargo
33	May 16, 2019	13:47	Sinar Maros III	General Cargo	Non-Class	Fire	4	Burn injuries
34	June 1, 2019	13:30	Lintas Timur	General Cargo	BKI	Sinking	1	Lack of flotation access
35	June 17, 2019	13:30	Arin Jaya	General Cargo	Non-Class	Sinking	21	Lack of flotation access
36	August 16, 2019	18:15	Izhar	Passenger	Non-Class	Fire	11	Lack of flotation access
37	August 22, 2019	20:25	Santika Nusantara	Ro-Ro Passenger	BKI	Fire	4	Burn injuries
38	May 11, 2020	08:30	Jag Leela	Tanker	BKI	Fire	7	Burn injuries
39	Feb 11, 2021	14:45	Gemilang Perkasa Energy	Tanker	BKI	Fire	3	Burn injuries
40	April 3, 2021	13:30	Habco Pioneer; Barokah Jaya	Bulk Carrier; Fishing Vessel	NK; Non-Class	Collision	4	Lack of flotation access
41	April 12, 2021	08:06	Asian Champion	Bulk Carrier	DNV	Other	1	Falling
42	May 15, 2021	11:30	Perahu Gako	Passenger	Non-Class	Sinking	9	Lack of flotation access
43	May 31, 2021	15:00	Ihan Batak	Ro-Ro Passenger	Non-Class	Other	1	Suffocation
44	June 29, 2021	19:06	Yunicee	Ro-Ro Passenger	BKI	Sinking	11	Delayed rescue
45	May 26, 2022	01:00	Ladang Pertiwi 02	Fishing Vessel	Non-Class	Sinking	4	Delayed rescue
46	June 8, 2022	21:45	Dumai Line 5	Passenger	Non-Class	Fire	2	Burn injuries
47	July 18, 2022	18:12	Cahaya Arafah	Passenger	Non-Class	Sinking	12	Delayed rescue
48	August 22, 2022	22:00	Teman Niaga	General Cargo	BKI	Sinking	3	Lack of flotation access
49	Sep 16, 2022	07:05	Sabuk Nusantara 91	Passenger	BKI	Fire	1	Evacuation obstruction
50	October 24, 2022	13:00	Ekspress Cantika 77	Passenger	BKI	Fire	20	Burn injuries

B. Distribution of Ship Accidents by Year

This subsection examines the temporal distribution of fatal ship accident cases in Indonesia during the period 2017–2022. Analyzing accident characteristics on an annual basis is essential for identifying fluctuation patterns and periods of increased accident concentration, which may reflect variations in traffic intensity, regulatory enforcement, operational practices, or external conditions.

The yearly distribution also provides an initial indication of whether fatal ship accidents occur sporadically or are clustered within specific time intervals, thereby supporting subsequent causal and risk-based analyses. By presenting both the number and proportion of accidents for each year, this analysis establishes a chronological framework for understanding the dynamics of ship accident occurrence and fatality exposure in Indonesian waters.

TABLE 2.
DISTRIBUTION OF SHIP ACCIDENTS BY YEAR

No	Year	Number of Accidents	Percentage (%)	Remarks
1	2017	9	18	Moderate number of fatal accidents
2	2018	20	40	Highest concentration of accidents
3	2019	8	16	Declining trend compared to 2018
4	2020	1	2	Significant reduction in accidents
5	2021	6	12	Gradual increase after 2020
6	2022	6	12	Stable level of accident occurrence
	Total	50	100	—

The results show that fatal ship accidents were unevenly distributed over the study period, with a pronounced peak in 2018, accounting for 40% of the total recorded cases. This concentration indicates a period of elevated operational risk or systemic vulnerability within Indonesian maritime transport during that year. A marked decline is observed in 2020, which may be associated with reduced maritime activity and operational restrictions, followed by a gradual stabilization in 2021 and 2022. Overall, the temporal pattern demonstrates that fatal ship accidents are not randomly distributed over time but instead exhibit distinct annual variations, warranting further investigation into the underlying causal and contextual factors influencing these trends.

C. Distribution of Ship Accidents by Time of Occurrence

This subsection presents the distribution of fatal ship accidents according to the time of occurrence, categorized into distinct time intervals to reflect operational and environmental variations throughout the day. Temporal classification is important in maritime safety analysis because navigational workload, visibility conditions, crew alertness, and emergency response effectiveness may differ substantially between nighttime, daytime, and evening operations. By grouping accident occurrences into time-based categories, this analysis provides insight into periods with elevated accident exposure and supports the identification of time-related risk patterns that may influence accident severity and fatal outcomes.

TABLE 3.
DISTRIBUTION OF SHIP ACCIDENTS BY TIME OF OCCURRENCE

No	Time Group	Number of Accidents	Percentage (%)	Remarks
1	Night (00:00–05:59)	12	24	Reduced visibility and crew fatigue
2	Morning (06:00–11:59)	14	28	High traffic during departure hours
3	Afternoon (12:00–17:59)	15	30	Peak operational and loading activities
4	Evening (18:00–23:59)	9	18	Transition period with declining visibility
	Total	50	100	—

The results indicate that fatal ship accidents occurred predominantly during daytime operations, particularly in the morning and afternoon periods, which together account for 58% of the total cases. This pattern suggests that accident occurrence is more strongly associated with high traffic density and intensive operational activities than with nighttime conditions alone. Nevertheless, a considerable proportion of accidents also took place during nighttime hours, indicating that reduced visibility, crew fatigue, and delayed emergency response remain significant contributing factors. Overall, the temporal distribution demonstrates that fatal ship accidents are influenced by both operational intensity and variations in human performance across different times of day, reinforcing the need for time-sensitive risk mitigation strategies in maritime operations.

D. Distribution of Ship Accidents by Vessel Type

This subsection analyzes the distribution of fatal ship accidents by vessel type in order to identify categories of ships that are more frequently associated with fatal outcomes. Vessel type is a key variable in maritime accident analysis because it reflects differences in operational patterns, passenger capacity, cargo characteristics, safety management systems, and levels of emergency preparedness. By examining accident occurrence across vessel categories, this section provides insight into structural and operational vulnerabilities that may influence accident severity and fatality risk, and it supports subsequent causal modeling using Fault Tree Analysis.

The results indicate that passenger vessels account for the largest proportion of fatal ship accidents, representing 40% of all cases during the study period, followed by Ro-Ro passenger vessels at 20%. This dominance reflects the greater number of individuals exposed to risk and the complexity of evacuation procedures during emergency situations. Cargo-related vessels, including general cargo ships, tankers, and bulk carriers, collectively contribute a substantial share of fatal accidents, demonstrating that fatal outcomes are not confined to passenger operations alone. Fishing vessels, although fewer in number, still exhibit a notable level of fatality risk, often associated with limited safety resources and inadequate emergency preparedness. Overall, this distribution underscores that vessel type plays a significant role in shaping accident severity and fatality exposure and should therefore be explicitly considered in risk assessment frameworks and preventive safety strategies.

TABLE 4.
DISTRIBUTION OF SHIP ACCIDENTS BY VESSEL TYPE

No	Vessel Type	Number of Accidents	Percentage (%)	Remarks
1	Passenger Vessels	20	40	High passenger exposure and evacuation challenges
2	Ro-Ro Passenger Vessels	10	20	Vehicle load and stability related risks
3	General Cargo Vessels	8	16	Operational and loading related accidents
4	Tankers	6	12	Fire and explosion prone cargo
5	Fishing Vessels	4	8	Limited safety equipment and small crew size
6	Bulk Carriers	2	4	Lower frequency but high consequence events
	Total	50	100	—

E. Distribution of Ship Accidents by Class

This subsection examines the distribution of fatal ship accidents according to vessel classification status in order to assess the influence of regulatory oversight and technical compliance on accident occurrence and severity. Vessel classification indicates the degree to which ships adhere to classification society standards concerning design, construction, maintenance, and safety management. Analyzing accident distribution by classification status provides valuable insight into whether classed vessels exhibit different risk characteristics compared with non-classed vessels, particularly with respect to fatal outcomes. This analysis contributes to a deeper understanding of the structural and governance-related factors that affect maritime safety performance.

TABLE 5.
DISTRIBUTION OF SHIP ACCIDENTS BY VESSEL CLASS

No	Vessel Class	Number of Accidents	Percentage (%)	Remarks
1	Non-Class	26	52	Limited regulatory oversight and safety compliance
2	BKI	19	38	National classification with standardized inspections
3	Other International Class	5	10	International standards with lower accident frequency
	Total	50	100	—

The results show that more than half of fatal ship accidents during the study period involved non classed vessels accounting for 52 percent of total cases. This finding suggests a strong association between the absence of formal classification and increased vulnerability to fatal accidents potentially due to weaker safety standards maintenance practices and inspection regimes. Vessels classified under the national classification society account for a substantial proportion of accidents reflecting their large presence in domestic operations rather than inherently higher risk. Accidents involving vessels under international classification societies are comparatively fewer indicating that higher compliance with international standards may contribute to reduced fatal accident occurrence. Overall the distribution highlights vessel class as an important factor in assessing maritime safety risk and underscores the need for strengthened regulatory control particularly for non classed vessels.

F. Fault Tree Analysis of Ship Accidents

In this study, the top event in the Fault Tree Analysis is defined as a fatal ship accident, namely a ship accident that results in loss of human life. The selection of this top event is justified by the empirical characteristics of the accident dataset, which consists of 50 ship accident cases recorded between 2017 and 2022, all of which involved fatalities with varying levels of severity. Rather than focusing solely on accident occurrence frequency, this study adopts fatality as the primary risk outcome to better represent accident severity and human safety impact. The dataset shows that fatalities occurred across multiple accident categories including collision, sinking, fire, grounding, and other operational incidents, indicating that loss of life is not confined to a single type of accident but emerges as a critical consequence of different accident pathways. By defining the top event as a fatal ship accident, the Fault Tree Analysis is able to systematically trace how combinations of human, technical, and environmental failures propagate through different incident categories and ultimately lead to loss of life, thereby providing a risk assessment framework that is explicitly oriented toward life safety rather than accident frequency alone.

G. Identification of Accident Categories as Intermediate

Events

In the Fault Tree Analysis framework, accident categories are defined as intermediate events that represent the main escalation pathways linking basic causal factors to the top event of a fatal ship accident. Based on the empirical fatality data from 2017 to 2022, five accident categories are identified, namely collision, fire, grounding, sinking, and other operational accidents. These categories are treated as intermediate events because they constitute distinct accident mechanisms through which fatalities occur and collectively account for all recorded loss of life in the dataset. The quantitative distribution of fatalities across accident categories demonstrates that loss of life is unevenly distributed, indicating varying levels of severity and escalation potential among different accident types. Sinking and fire accidents emerge as the most critical intermediate events due to their disproportionately high fatality counts, while collision and grounding events frequently act as initiating or transitional failures that may escalate into more severe outcomes. Logically, each intermediate event is connected to the top event through an OR-gate relationship, meaning that the occurrence of any one accident category is sufficient to result in a fatal ship accident when accompanied by specific contributing factors.

TABLE 6.
FATALITY DISTRIBUTION BY ACCIDENT CATEGORY AND CAUSE OF DEATH

Accident Category	Cause of Death	Fatalities
Collision	Crushed by cargo	1
	Delayed rescue	5
	Lack of flotation access	1
	Lack of flotation access	4
Total Fatalities by Collision		11
Fire	Burn injuries	46
	Evacuation obstruction	2
	Explosion pressure	1
	Falling	5
	Gas poisoning	24
	Lack of flotation access	24
Total Fatalities by Fire		102
Grounding	Evacuation obstruction	6
	Unable to swim	34
Total Fatalities by Grounding		40
Sinking	Delayed rescue	32
	Evacuation obstruction	18
	Lack of flotation access	69
	Suffocation	3
Total Fatalities by Sinking		122
Other	Burn injuries	5
	Crushed by cargo	6
	Falling	2
	Gas poisoning	6
	Suffocation	1
Total Fatalities by Other		20
Total Fatalities		295

The fatality distribution clearly indicates that sinking accidents represent the most severe intermediate event, accounting for 122 fatalities or approximately 41 percent of total deaths, followed closely by fire related accidents with 102 fatalities or 35 percent. These two categories together contribute more than three quarters of total fatalities, highlighting their dominant role in fatal ship accident escalation. Collision and grounding accidents account for smaller but still significant shares of fatalities and often involve indirect fatal mechanisms such as delayed rescue evacuation obstruction and lack of flotation access rather than immediate impact trauma. This pattern confirms that fatalities are primarily driven by escalation dynamics and post accident survivability rather than the initial accident type alone. Defining accident categories as intermediate events in the FTA structure therefore enables the model to capture multiple fatality pathways and provides a robust foundation for tracing how different combinations of contributing factors lead to loss of life.

H. Identification of Contributing Factors as Basic Events

In the Fault Tree Analysis framework, basic events represent the most fundamental contributing factors that directly lead to accident escalation and ultimately to loss of life. Using the empirical fatality data presented in Table 4.6, causes of death are systematically translated into basic events and grouped into three principal categories, namely human factors, technical factors, and environmental and external factors. This classification ensures that the fault tree structure is grounded in observed accident outcomes rather than theoretical assumptions. Each basic event reflects a specific failure at the lowest level of the fault tree that contributes to fatal ship accidents across different incident categories.

Human factors emerge predominantly through causes of death related to emergency response and survivability such as delayed rescue evacuation obstruction lack of flotation access and inability to swim. Technical factors are reflected by fatalities caused by burn injuries explosion pressure gas poisoning and crushing by cargo which indicate failures in ship systems equipment cargo securing or hazardous material control. Environmental and external factors include falling and suffocation where external conditions or post accident environments significantly reduce survival chances. By quantifying fatalities associated with each basic event, the FTA model captures both the causal mechanism and its severity contribution to the top event of fatal ship accidents.

TABLE 7.
MAPPING OF CAUSES OF DEATH TO FTA BASIC EVENTS AND FATALITIES

Contributing Factor Category	Cause of Death	FTA Basic Event	Number of Fatalities
Human Factors	Delayed rescue	Ineffective emergency response	69
	Evacuation obstruction	Evacuation failure	26
	Lack of flotation access	Insufficient life saving appliances	99
	Unable to swim	Passenger preparedness failure	34
Technical Factors	Burn injuries	Fire system failure	60
	Explosion pressure	Explosion hazard	1
	Gas poisoning	Toxic gas exposure	60
	Crushed by cargo	Cargo securing failure	14
Environmental and External Factors	Falling	Loss of balance or external impact	12
	Suffocation	Oxygen depletion or confined space exposure	5
	Total Fatalities		295

The fatality distribution at the basic event level clearly demonstrates the dominance of human factors, particularly insufficient access to flotation devices and delayed rescue, which together account for more than half of total fatalities. Technical factors such as fire related system failures and toxic gas exposure also contribute substantially to loss of life, especially in fire and explosion incidents. Environmental and external factors, although less frequent, remain critical in determining survivability once an accident has occurred. Incorporating both causal classification and fatality magnitude into the identification of basic events strengthens the Fault Tree Analysis by enabling subsequent qualitative identification of minimal cut sets and quantitative estimation of the most critical pathways leading to fatal ship accidents.

I. Construction of the Fault Tree Diagram

This subsection presents the construction and visualization of the Fault Tree Analysis diagram developed to model the causal structure of fatal ship accidents in Indonesia. The fault tree is built by integrating the top event intermediate accident categories and basic contributing factors derived from empirical investigation data and fatality records. The diagrams illustrate how different categories of ship accidents and underlying failures interact logically to produce fatal outcomes and provide a clear graphical representation of accident escalation pathways that support both qualitative and quantitative analysis.

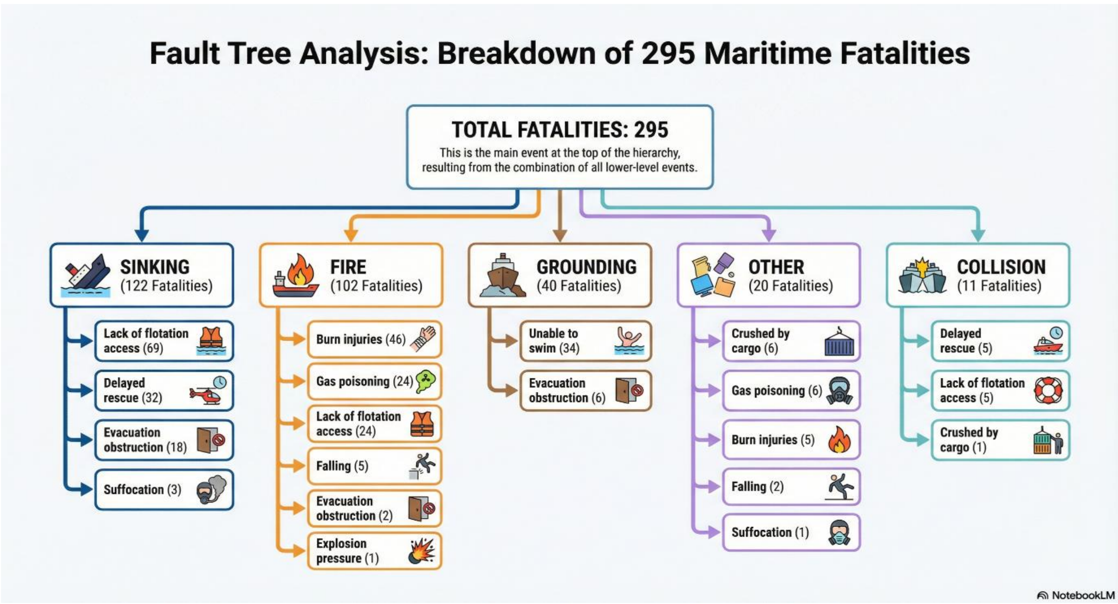

Figure 2. Fault Tree Analysis Breakdown of 295 Maritime Fatalities by Accident Category

Figure 2 presents an alternative fault tree representation that organizes fatalities according to accident categories acting as intermediate events namely sinking fire grounding other operational accidents and collision. The diagram clearly demonstrates that sinking and fire accidents dominate fatal outcomes accounting for 122 and 102 fatalities respectively while grounding other accidents and collision contribute smaller shares. Each accident category is further decomposed into specific causes of death which correspond to basic events such as lack of flotation access delayed rescue burn injuries gas poisoning and evacuation obstruction. This representation highlights that fatalities are not solely determined by the initial accident type but by the interaction between accident categories and post accident survivability factors. The diagram reinforces the logical OR relationship between intermediate events and the top event indicating that any accident category can lead to loss of life when critical basic events are present thereby validating the hierarchical structure of the proposed Fault Tree Analysis model.

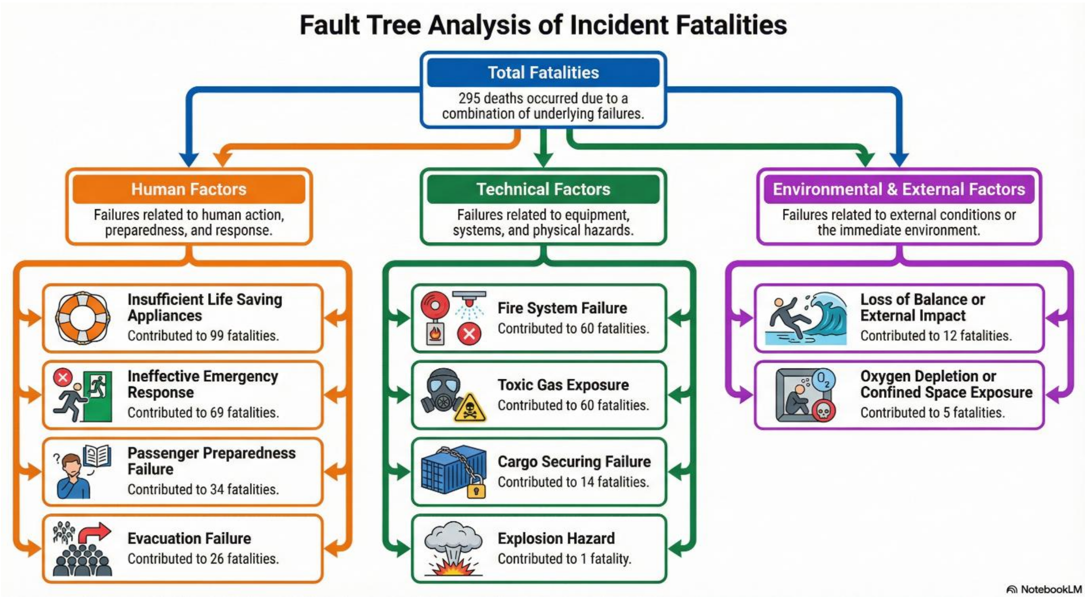

Figure 3. Fault Tree Analysis of Incident Fatalities Based on Contributing Factors

Figure 3 illustrates the fault tree structure focusing on the decomposition of total fatalities into three main groups of basic contributing factors namely human factors technical factors and environmental and external factors. The diagram shows that a total of 295 fatalities resulted from a combination of these underlying failures rather than from a single isolated cause. Human factors constitute the most dominant branch with insufficient life saving appliances ineffective emergency response passenger preparedness failure and evacuation failure contributing the largest share of fatalities. Technical factors form the second major branch dominated by fire system failure and toxic gas exposure while cargo securing failure and explosion hazards play a smaller but still critical role. Environmental and external factors such as loss of balance external impact and oxygen depletion or confined space exposure contribute fewer fatalities but significantly affect survivability once an accident has occurred. This structure confirms that fatal ship accidents are primarily driven by compounded human and technical failures with environmental conditions acting as amplifying elements.

J. Qualitative and Quantitative Fault Tree Analysis of Fatal Ship Accidents

This subsection integrates qualitative and quantitative Fault Tree Analysis to identify dominant failure pathways and to assess the relative contribution of basic events to fatal ship accidents. The qualitative analysis focuses on identifying dominant failure paths and minimal cut sets, defined as the smallest combinations of basic events sufficient to trigger the top event of a fatal ship accident. The quantitative analysis complements this approach by estimating the probability contribution of each basic event using historical fatality frequencies, allowing the evaluation of risk significance across human, technical, and environmental factors. This integrated analysis provides a comprehensive understanding of how accident escalation occurs and which combinations of failures most critically affect loss of life.

The qualitative Fault Tree Analysis reveals that fatal ship accidents are predominantly driven by single-point survivability failures, particularly those related to human factors rather than complex combinations of multiple simultaneous failures. Minimal cut sets such as lack of flotation access and delayed rescue independently constitute sufficient conditions to result in fatal outcomes once an accident occurs, regardless of the initiating accident category. These findings indicate that accident severity is strongly influenced by post-accident response capability and access to life-saving resources rather than the initial triggering event alone. Fire-related basic events also emerge as critical cut sets, where technical failures rapidly escalate accident consequences through thermal hazards and toxic environments.

From a quantitative perspective, human-factor-related basic events account for the largest share of fatality risk, with insufficient life-saving appliances and ineffective emergency response together contributing more than 57 percent of total fatalities. Technical factors, particularly fire system failure and toxic gas exposure, contribute approximately 40 percent of fatalities, highlighting their substantial but secondary role compared to human factors. Environmental and external factors contribute a smaller proportion but remain important as amplifiers of fatality risk once survivability thresholds are crossed. Overall, the integrated qualitative and quantitative FTA results demonstrate that fatal ship accidents are primarily the result of dominant, high-impact basic events rather than rare combinations of multiple failures, underscoring the importance of prioritizing life-saving equipment availability, emergency response effectiveness, and fire safety systems in maritime risk mitigation strategies.

TABLE 8
DOMINANT MINIMAL CUT SETS AND PROBABILITY CONTRIBUTION OF BASIC EVENTS

No	Minimal Cut Set (Basic Events Combination)	Accident Escalation Mechanism	Fatalities	Probability Contribution
1	Lack of flotation access	Survivability failure after accident	99	0.336
2	Delayed rescue	Ineffective emergency response	69	0.234
3	Fire system failure	Rapid escalation of fire incidents	60	0.203
4	Toxic gas exposure	Lethal post-fire environment	60	0.203
5	Evacuation failure	Congestion and blocked escape routes	26	0.088
6	Passenger preparedness failure	Inability to self-rescue	34	0.115
7	Cargo securing failure	Impact-related fatalities	14	0.047
8	Environmental exposure (falling, suffocation)	Reduced post-accident survivability	17	0.058
	Total		295	1.000

K. Importance and Contribution Ranking of Risk Factors

This subsection presents the importance and contribution ranking of risk factors associated with fatal ship accidents based on the results of the integrated qualitative and quantitative Fault Tree Analysis. The ranking is derived from the probability contribution of each basic event, calculated using historical fatality data, and reflects the relative influence of each factor in leading to the top event of loss of life. This approach enables prioritization of risk factors according to their actual impact on fatality outcomes rather than theoretical likelihood alone, thereby strengthening the practical relevance of the analysis for safety management and preventive decision making.

TABLE 9
IMPORTANCE RANKING OF BASIC EVENTS BASED ON FATALITY CONTRIBUTION

Rank	Basic Event	Contributing Factor Category	Fatalities	Probability Contribution
1	Insufficient life-saving appliances	Human factors	99	0.336
2	Ineffective emergency response (delayed rescue)	Human factors	69	0.234
3	Fire system failure	Technical factors	60	0.203
4	Toxic gas exposure	Technical factors	60	0.203
5	Passenger preparedness failure	Human factors	34	0.115
6	Evacuation failure	Human factors	26	0.088
7	Environmental exposure (falling, suffocation)	Environmental and external factors	17	0.058
8	Cargo securing failure	Technical factors	14	0.047
	Total		295	1.000

The importance ranking clearly demonstrates that human-related factors dominate the fatality risk profile of ship accidents in Indonesia. Insufficient access to life-saving appliances emerges as the most critical risk factor, contributing more than one-third of total fatalities, followed by ineffective emergency response characterized by delayed rescue operations. These findings indicate that once an accident occurs, survivability is primarily determined by the availability of safety equipment and the effectiveness of emergency management rather than by the initiating accident mechanism itself. Passenger preparedness failure and evacuation failure further reinforce the central role of human performance and safety culture in shaping fatal outcomes.

Technical factors occupy the second tier of importance, with fire system failure and toxic gas exposure jointly accounting for over 40 percent of fatalities. This highlights the severe escalation potential of fire-related accidents and the critical role of onboard fire protection and ventilation systems in preventing loss of life. Environmental and external factors, although ranked lower, still contribute meaningfully by exacerbating post-accident conditions and reducing survival chances. Overall, the ranking confirms that risk mitigation strategies should prioritize human-centered interventions, particularly improvements in life-saving appliance availability, emergency response capability, and passenger preparedness, complemented by robust technical fire safety systems. This prioritization provides a clear evidence-based foundation for maritime safety policy formulation and targeted risk reduction measures.

L. Discussion

The The results of this study offer a deeper understanding of fatal ship accidents in Indonesia by revealing that mortality is governed primarily by failures in post-accident survivability rather than by the initiating accident mechanisms themselves. This indicates that the transition phase between accident occurrence and emergency response represents a critical vulnerability window in which relatively small deficiencies in preparedness or system performance can rapidly escalate into mass-casualty events. In this context, sinking and fire are not merely accident outcomes but act as amplification mechanisms that convert manageable incidents into catastrophic disasters. Their dominance as intermediate events contributing to more than three quarters of total fatalities demonstrates that fatality formation is driven by escalation dynamics rather than by the original hazard source.

A key novel insight of this study is the identification of lack of flotation access and delayed rescue as the most dominant basic events. These findings suggest that survival probability is strongly determined by time-dependent factors: the availability of immediate buoyancy support and the speed of external assistance. In Indonesian maritime operations, where voyages often occur in remote or congested waters and where communication and coordination infrastructure may be limited, delays in rescue efforts substantially increase exposure to drowning, hypothermia, and exhaustion. This highlights a structural vulnerability in the maritime safety system, whereby even non-catastrophic accidents can become fatal due to the absence of rapid survivability pathways. Unlike previous studies that conceptualize evacuation failure broadly, this study isolates specific operational breakdowns that directly control fatality risk, thereby providing more actionable targets for intervention [2], [12], [16].

The dominance of human-related basic events further reflects the systemic nature of maritime accidents, in which human operators function as both safety barriers and potential points of failure. Insufficient life-saving appliances, ineffective emergency response, evacuation failure, and passenger preparedness failure together account for more than half of the fatalities, indicating that accident outcomes are shaped less by technical malfunction alone and more by the interaction between human decision-making, training quality, and organizational safety culture. This finding supports the view that maritime safety is not solely an engineering problem but a socio-technical challenge. In many Indonesian passenger vessel operations, overcrowding, informal boarding practices, and limited safety drills weaken the reliability of human-centered safety barriers, increasing the likelihood that emergency procedures will fail under stress. Thus, fatalities emerge not as isolated errors but as predictable consequences of latent organizational conditions [8], [10], [14]. Technical factors particularly fire system failure and toxic gas exposure constitute the second most influential group of contributors. Fire accidents represent a distinct class of hazards due to their rapid escalation speed and the compounding effects of confined shipboard geometry. The accumulation of smoke and toxic gases can incapacitate passengers and crew within minutes, rendering evacuation physically impossible even when escape routes are theoretically available. This study deepens existing knowledge by showing that technical system failure primarily influences fatality risk through its impact on survivability rather than on accident initiation. When detection, suppression, and ventilation systems fail simultaneously, the ship environment transforms into an uninhabitable space, making human response capacity irrelevant. This interaction between technical breakdown and human vulnerability explains why fire scenarios yield disproportionately high fatality rates compared with collision or grounding accidents [7], [9].

The comparatively lower contribution of collision and grounding accidents should be interpreted as a difference in causal pathways rather than as evidence of lower danger. These events serve mainly as initiating triggers that propagate through indirect mechanisms such as progressive flooding, loss of stability, blocked evacuation routes, and rescue delays [15], [22].

This study demonstrates that fatalities rarely result from the physical impact of collision itself but from the subsequent breakdown of safety barriers. This supports the structural logic of the Fault Tree Analysis model, in which collision and grounding are positioned as intermediate events connected to the top event through escalation pathways. Such a structure reflects real-world accident evolution, where initial damage evolves into secondary hazards that ultimately determine survival outcomes [6], [27], [28].

From a theoretical perspective, this study contributes to accident causation research by empirically validating systemic hazard models that emphasize barrier failure and escalation control over linear cause–effect relationships. The findings indicate that fatal ship accidents are dominated by a small number of high-impact basic events rather than by complex combinations of multiple low-probability failures. This challenges traditional prevention-focused paradigms that prioritize reducing accident frequency alone and instead supports a resilience-oriented framework that focuses on strengthening survivability capacity after accidents occur [3], [11], [29]. From a practical and policy standpoint, the results imply that the most effective risk reduction strategies lie in improving emergency preparedness, evacuation management, and life-saving appliance accessibility rather than solely investing in navigational or collision-avoidance technologies. Enhancing crew training, enforcing passenger safety briefings, ensuring adequate flotation devices, and improving rescue coordination systems may yield disproportionately large reductions in fatalities. In the Indonesian maritime context, where passenger transport remains a critical mode of mobility, these measures are particularly urgent. By reframing fatal ship accidents as failures of survivability systems rather than merely as operational mishaps, this study provides a new analytical lens for maritime regulators and operators seeking to achieve meaningful reductions in loss of life.

IV. CONCLUSION

This study concludes that fatal ship accidents in Indonesia are primarily determined by failure mechanisms related to post-accident survivability rather than by the initial accident triggers alone. The developed Fault Tree Analysis (FTA) model successfully integrates accident incident categories with fatality factors and demonstrates that sinking and fire function as the most critical intermediate events leading to loss of life. Human-related factors particularly insufficient access to life-saving appliances, delayed rescue, evacuation failure, and inadequate passenger preparedness emerge as the dominant basic events contributing to more than half of total fatalities. These findings confirm that accident severity should be assessed not only in terms of occurrence frequency but also through its fatal consequences, emphasizing the importance of emergency response effectiveness and escalation control in determining overall maritime accident risk.

Furthermore, the results show that technical failures, especially fire system malfunction and toxic gas exposure, constitute the second most significant contributors to fatal accidents, while collision and grounding mainly serve as initiating events that escalate into more severe outcomes such as sinking and fire through indirect causal pathways. The identification of critical minimal cut sets indicates that fatal accidents are largely driven by dominant high-impact causal factors rather than by complex combinations of multiple low- probability failures. Overall, the proposed FTA-based risk assessment model provides a robust analytical foundation for preventive decision making, enabling targeted risk mitigation strategies that prioritize human-centered interventions, emergency preparedness, and fire safety systems. This approach offers valuable support for maritime safety policies oriented toward reducing loss of life and strengthening life-safety-focused risk management in maritime transportation systems.

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