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Applying Formal Safety Assessment (FSA) to Fishing Vessels: An Analysis of Occupational Injuries on Korean Trap Boats

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Abstract: Fishing vessels are known to have a fatality rate from accidents nearly 100 times higher than that of merchant ships. However, since most cases are resolved internally without maritime tribunals, obtaining accurate statistics on accidents is challenging, making quantitative analysis and evaluation of accident risks difficult. Studies using inconsistent analytical methods often fail to converge on unified results or preventive measures, which contributes to the persistently high occurrence of fishing vessel accidents. Therefore, this study aimed to establish a standardized method for analyzing marine accidents on fishing vessels by applying the Formal Safety Assessment (FSA) technique, originally developed for merchant ships. The research focuses on the globally prevalent trap boat fishery, specifically examining common injuries occurring on fishing vessels. Quantitative data were collected from insurance approval records, while qualitative data were obtained through surveys. The research followed the five stages of the FSA framework: hazard identification, risk estimation, identification of risk control options, cost-benefit assessment, and recommendations for decision-making. The findings suggest that the FSA framework can be effectively applied to analyze fishing vessel accidents based on insurance data, leading to selective and effective preventive measures.

Keywords: formal safety assessment; occupational injuries; trap boat fisheries; fishing vessels

Key Contribution: Occupational injuries occurring on fishing vessels were analyzed using the Formal Safety Assessment (FSA) technique proposed for merchant ships. If sufficient quantitative data on accident occurrences (such as the number of incidents, types of injuries, etc.) can be obtained, reliable results can be derived.

Academic Editor: Tsutomu Takagi

Received: 16 December 2024
Revised: 3 January 2025
Accepted: 9 January 2025
Published: 14 January 2025

Citation: Kim, S.-H.; Lee, S.-H.; Ryu, K.-J.; Lee, Y.-W. Applying Formal Safety Assessment (FSA) to Fishing Vessels: An Analysis of Occupational Injuries on Korean Trap Boats. *Fishes* **2025**, *10*, 30. https://doi.org/10.3390/fishes10010030

1. Introduction

It is estimated that approximately 39 million fishermen worldwide are engaged in capture fisheries [1]. Fishing is considered one of the most hazardous occupations globally [2]. Although precise statistics are not available, reports indicate that over 32,000 fatalities occur annually on fishing vessels [1], a number approximately 100 times higher than that for merchant ships [3]. In contrast, a review of treaties related to vessel safety and crew welfare reveals significant regulatory gaps for fishing vessels. For merchant ships, conventions such as SOLAS 1974 (Safety of crew), STCW 1978 (Training), LL 1996 (Stability), COLREGs 1972 (Collisions), MLC 2006 (Labor standards), and MARPOL 1973/78 (Environmental protection) are in effect. However, for fishing vessels, only STCW-F 1995 (Training), C188

2007 (Labor standards), and PSMA 2009 (Environmental protection) have been ratified, two of which came into effect after 2000 [4].

Recently, the sinking of the trawler 501 Oryong in the western Bering Sea in 2014 resulted in 53 casualties, including 26 missing persons [5], illustrating how fishing vessel accidents, due to the nature of their operations and the large number of crew members on board, are directly linked to severe human casualties. From the perspective of preventing human casualties, accidents on fishing vessels should be prioritized above all else.

Studies conducted to prevent fishing vessel accidents so far can be categorized based on their methodologies. Representative studies include those that focus on analyzing the causes of maritime accidents involving specific vessels to derive conclusions [5–7]; studies that classify and quantitatively analyze the types of accidents on fishing vessels using accident statistics [8–11]; studies that estimate the occurrence rates of direct or indirect factors contributing to accidents using statistical analysis and predictive techniques such as Bayesian networks or fault tree analysis (FTA), leading to proposed preventive measures [12–14]; and studies that combine quantitative findings with qualitative analyses derived from expert opinions to suggest more practical preventive measures [15].

However, unlike merchant ships, fishing vessel accident analysis lacks clearly established criteria, making it difficult to derive consistent results. Consequently, research findings often vary in different directions, hindering a reduction in accident rates. The lack of clear standards for accident causes and outcomes leads researchers to apply various methodologies, and as a result, the preventive measures proposed may not achieve practical effectiveness. Furthermore, there are also significant differences between merchant ships and fishing vessels regarding the quantity and quality of data available for accident-related research. For merchant ships, the financial and environmental damages caused by accidents tend to be more severe, resulting in most cases being brought before maritime tribunals, which facilitates the accumulation of clear data on causes and outcomes. In contrast, accidents on fishing vessels are primarily related to loss of life, with many cases being resolved internally, leading to a relative lack of detailed analytical data on their causes and outcomes. This lack of quantitative data necessitates making numerous assumptions during research, and the preventive measures proposed based on such findings often fail to provide practical solutions. This challenging research environment may explain why the occurrence rate of fishing vessel accidents has not decreased over time.

In this context, the authors identified the need for a standardized formal methodology to analyze fishing vessel accidents and applied the FSA technique [16], as proposed by the IMO, to quantitatively assess incidents on fishing vessels. This research was conducted as a preliminary study to validate whether the FSA technique, originally developed for merchant ships, is suitable for analyzing occupational incidents on fishing vessels. This study focused on trap boats, which are widely distributed worldwide, and was conducted based on vessels registered in Korea, where clear data could be obtained. It assumes, however, that the work processes and operational patterns of most trap boats are similar. Quantitative data were collected from insurance approval records, while qualitative data were obtained through surveys. The research followed the five stages of the FSA framework: hazard identification, risk estimation, identification of risk control options, cost–benefit analysis, and recommendations for decision-making.

2. Materials and Methods

2.1. Occupational Injury Data

The data used in this study are limited to incidents that occurred in trap boat fisheries in South Korea. It should be noted that the nature of injuries may vary depending on the fishing practices in different countries. Nevertheless, as this study aims to standardize and formalize methods and processes for analyzing accidents on fishing vessels using the IMO's FSA framework, it serves as a valuable reference for future research. In particular, this study contributes to validating the applicability of the FSA technique to fishing vessel accident analysis.

2.1.1. Target Industry

This study focused on occupational injuries occurring during fishing operations using trap boats (Figure 1). The selection of this focus is based on several reasons. A review of industrial injury compensation approval data for fishing operations over the past five years (2016–2020) revealed that accidents involving trap boats ranked third among all types of fisheries yet had the highest fatality rate per incident (Table 1) [14,17]. Additionally, despite variations in fishing practices between countries, trap fishing is a widely employed method globally, enhancing the relevance and applicability of the research process and findings.

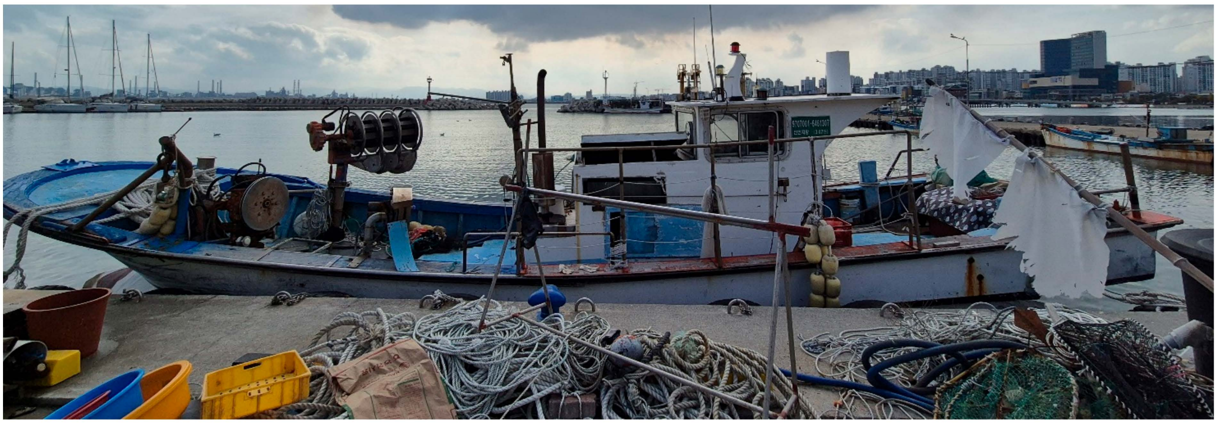


Figure 1. Side view of a trap fishing vessel.

Table 1. Industrial injury statistics in fishing operations in Korea (2016–2020) under the Seafarers' and Fishing Vessel's Accident Compensation Act. Unit: Cases (%).

Type of Fisheries	Number of Cases	Fatalities	Fatality Rate per Case
Gill-netter	3753	159	(4.02)
Purse seiner	1864	43	(2.31)
Trap boat	1790	87	(4.86)
Composite fishing boat	1502	39	(2.60)
Stow netter	1419	58	(4.09)
Others	4345	202	(4.65)
Total	14,873	588	(3.95)

2.1.2. Quantitative Data (Compensation Payment Records)

In cases where major accidents, such as collisions or capsizing, result in multiple casualties on fishing vessels, the incidents are referred to maritime tribunals [18]. However, many common occupational injuries in fishing operations often go unrecorded in statistics, making it challenging to secure quantitative data on the causes and outcomes of such incidents [19]. To address this issue, the authors obtained compensation payment records from the National Federation of Fisheries Cooperatives (SUHYUP), a Korean government-affiliated agency [20]. These records, which cover 6463 registered fishing vessels over the past five years, provide comprehensive details on the causes, outcomes, and compensation amounts related to occupational injuries on fishing vessels, making them a valuable source of quantitative data for this study.

2.1.3. Qualitative Data (Expert Surveys)

This study surveyed and interviewed 101 fishermen engaged in trap boat fisheries targeting species such as eels and crabs [14,21]. Only responses with complete answers to all questions were included, resulting in usable data from 90 respondents. The respondents were categorized by their years of experience as follows: less than 10 years (6 participants), 10 to less than 20 years (19 participants), 20 to less than 30 years (26 participants), and 30 years or more (39 participants). This distribution was considered to represent a sufficiently experienced expert group.

Survey Design (IMO Human Element)

It is widely acknowledged that most maritime accidents are caused by the human element, with preventive measures typically focusing on crew education and training. However, the IMO has determined that the human element involves not only individual human issues but also a complex interplay of multiple factors. It classified the factors influencing the human element into six categories for maritime accident investigations: People factors, Organization on board, Working and living conditions, Ship factors, Shore-side management, and External influences and environment [22]. Figure 2 illustrates the six factors related to the human element as proposed by the IMO.

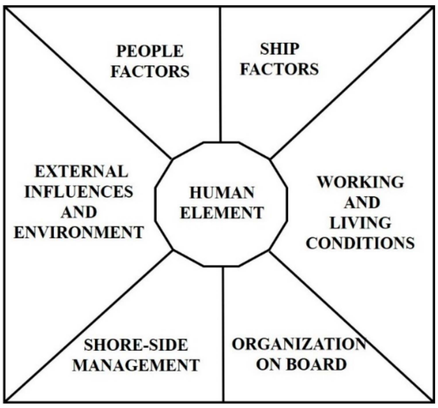


Figure 2. Six factors affecting the IMO human element in maritime accident investigation.

Each of the six factors is composed of several sub-factors; this study used these sub-factors to design the survey questions (Figure 3). To aid the fishermen's understanding, each sub-factor was presented with appropriate examples.

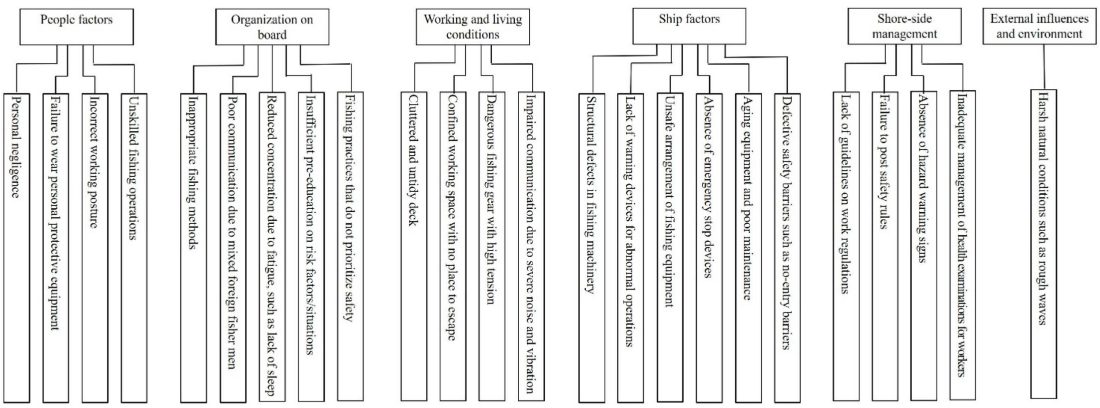


Figure 3. Sub-factors of the six categories of the IMO human element.

2.2. Formal Safety Assessment (FSA)

This study applied the FSA technique to analyze fishing vessel accidents using a standardized methodology, with the goal of providing structured and reliable results for preventive measures against risks. The FSA is a structured, systematic methodology designed to enhance maritime safety, including the protection of life, health, the marine environment, and property, through risk analysis and cost–benefit assessments [16]. The primary objective of the FSA technique is to develop a clear, cost-effective framework for addressing risks and establishing safety requirements for ships [23]. Moreover, the FSA methodology can be used to evaluate both new and existing regulations [24]. It is particularly valuable as a comparative tool for assessing current and proposed regulations, helping to balance technical and operational issues, including human factors and the costs associated with implementing safety measures [25].

As outlined below, the FSA methodology consists of five stages, which formed the basis of this study:

1. Identification of hazards
2. Risk estimation
3. Identification of risk control options
4. Cost-benefit assessment
5. Recommendations for decision-making.

2.2.1. Risk Matrix Approach

To apply the FSA technique, it is essential to classify the collected occupational injury data according to risk rankings. The Risk Matrix approach defines risk levels by considering both the frequency and severity of occupational injuries, allowing for a clear evaluation of each risk. This approach, recommended by the FSA, is a widely recognized and reliable method in risk management, endorsed by international standards such as those provided by the International Electrotechnical Commission (IEC) [26] and International Organization for Standardization (ISO) [15,27].

In this study, the frequency and severity of injuries were categorized into five scales, as shown in Tables 2 and 3. Specifically, since the focus was on fishing vessel injuries, the frequency scale was determined based on the probability of occurrence for each of the 29,183 insured individuals over five years (Table 2) [28], while the severity scale was assigned according to compensation amounts, divided into intervals (Table 3) [29]. For calculation purposes, 1000 KRW was treated as equivalent to 1 USD.

Table 2. Frequency assignment for the Risk Matrix approach. Unit: Years.

Assigned Rating	Likely to Happen on One Boat
F1 (10,000–100,000)	Extremely remote to extremely improbable
F2 (1000–10,000)	Remote to extremely remote
F3 (100–1000)	Remote
F4 (10–100)	Reasonably probable to remote
F5 (1–10)	Reasonably probable

By combining frequency and severity, the risk ranking number (RRN) for each injury can be determined [30], enabling an evaluation of the risk level. Table 4 below presents the Risk Matrix, which combines the frequency data from Table 2 and the severity data from Table 3 to indicate the risk level of each injury. The risk level is assessed using the

RRN, which ranges from a minimum value of 1 to a maximum value of 9, based on both frequency and severity.

Table 3. Consequence severity assignment for the Risk Matrix approach. Unit: USD.

Assigned Rating	Compensation Payment Amount
S1 (Negligible)	Less than 10,000
S2 (Minor)	10,000–less than 50,000
S3 (Significant)	50,000–less than 100,000
S4 (Critical)	100,000–less than 300,000
S5 (Catastrophic)	300,000 or more

Table 4. Risk Matrix representing risk levels. Unit: Number.

Severity \ Frequency	F1	F2	F3	F4	F5
S1 (Negligible)	1	2	3	4	5
S2 (Minor)	2	3	4	5	6
S3 (Significant)	3	4	5	6	7
S4 (Critical)	4	5	6	7	8
S5 (Catastrophic)	5	6	7	8	9

2.2.2. Fault Tree Analysis (FTA)

FTA, a risk analysis technique proposed in the FSA, is a graphical modeling method used to investigate the root causes of system failures and malfunctions at various levels [31]. This technique enables a quantitative analysis of the key sub-factors influencing the priority risks identified through the Risk Matrix approach. Specifically, the causes of injuries and the factors influencing them can be analyzed both quantitatively and probabilistically, with injury causes expressed as probabilities. This approach allows for targeted and systematic accident prevention efforts. Additionally, the FTA offers the advantage of visually illustrating the relationships between direct and indirect causes of injuries, providing a comprehensive view of the links between the nature of accidents and their underlying factors [32].

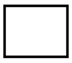
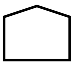
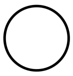
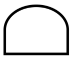
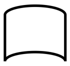
Procedures

Using the quantitative and qualitative data collected, the causes and outcomes of injuries are analyzed both quantitatively and qualitatively. The priority of injuries, as classified in the Risk Matrix, is used to select the top event. From this point, the analysis proceeds to the basic events (e.g., indirect factors, including final elements) and connects them with logical gates to construct a fault tree (FT) diagram. The next step involves calculating the occurrence rates of events through FT quantification, followed by conducting a risk assessment [33].

Symbols and Terminology

Table 5 below presents the symbols and terms used in this study. Although FTA includes numerous symbols and terms, this study employs only the basic terms necessary for constructing FT diagrams as part of the FSA process to aid reader comprehension.

Table 5. Fault tree symbols and descriptions.

Symbols	Name	Description
	Intermediate event	An event that occurs as a result of one or more preceding events within a fault tree analysis.
	External event	An event that is outside the control of the system being analyzed and is assumed to occur independently.
	Basic event	A fundamental event that does not need further development within the fault tree.
	AND Gate	A logical gate in fault tree analysis where the output event occurs only if all input events occur simultaneously.
	OR Gate	A logical gate in FTA where the output event occurs if at least one of the input events occurs.

3. Formal Safety Assessment

3.1. Step 1. Identification of Hazards

Hazard identification is a systematic process for identifying events associated with risks that may result in significant consequences for personnel, the environment, or assets [15]. In this study, the compensation payment records presented in Section 2.1.2 were used to identify hazard priorities. The terms related to the types of occupational injuries applied in this study follow the classification system for accident types designated by the Korea Occupational Safety and Health Agency (KOSHA), which categorizes incidents into forms such as Trip, Slip, Bump, Hit, Stuck, and Fall [34].

3.1.1. List of Injuries

A quantitative analysis of 1790 injuries that occurred on 6463 trap fishing vessels registered over the past five years revealed that Trip/Slip (511 cases, 28.5%), Bump/Hit (390 cases, 21.8%), and Stuck (319 cases, 17.8%) were significantly more frequent than other types of injuries (Table 6). Therefore, this study classified the aforementioned three injury types as priority risk groups. However, "Others" was excluded from the priority group because it was recorded as "unknown causes."

Table 6. Breakdown of injuries by type according to the industrial accident codes designated by Korea occupational safety and health agency. Unit: Cases (%).

Injury Type \ Year	2016	2017	2018	2019	2020	Total
Trip/Slip	100	106	112	105	88	511 (28.5)
Stuck	64	61	75	62	57	319 (17.8)
Bump/Hit	82	83	69	91	65	390 (21.8)
Falling from height	19	27	21	18	12	97 (5.4)
Crumble/ Crushed	2	3	1	2	1	9 (0.5)

Table 6. *Cont.*

Injury Type \ Year	2016	2017	2018	2019	2020	Total
Unnatural posture	17	22	18	29	23	109 (6.1)
Exposure to extreme temperatures	0	8	2	2	4	16 (0.9)
Exposure to chemicals	10	7	17	13	9	56 (3.1)
Others	51	67	58	66	41	283 (15.8)
Total	345	384	373	388	300	1790 (100.0)

Additionally, an analysis of injury occurrences by compensation amount is shown below (Table 7).

Cases under \$10,000 accounted for the highest proportion (928 cases, 51.8%), followed by \$10,000–\$50,000 (575 cases, 32.1%) and \$50,000–\$100,000 (183 cases, 10.2%). Similarly, "Others" was excluded for the same reasons as in the breakdown by injury type.

Table 7. Breakdown of injuries by compensation amount. Units: USD, Cases (%).

Injury Type \ Compensation Amount	Less than \$10,000	\$10,000–\$50,000	\$50,000–\$100,000	\$100,000–\$300,000	More than \$300,000	Total
Trip/Slip	297	172	34	8	0	511
Stuck	140	121	47	11	0	319
Bump/Hit	207	136	34	12	1	390
Falling from height	40	30	21	6	0	97
Crumble/Crushed	5	4	0	0	0	9
Unnatural posture	49	45	13	2	0	109
Exposure to extreme temperatures	11	4	1	0	0	16
Exposure to chemicals	38	12	4	1	1	56
Others	141	51	29	58	4	283
Total	928 (51.8)	575 (32.1)	183 (10.2)	98 (5.5)	6 (0.3)	1790 (100.0)

3.1.2. Injury Screening

The hazard screening process employed the Risk Matrix approach, as detailed in Section 2.2.1. Risk Matrix tables are typically developed by incorporating expert opinions. In this study, the Risk Matrix table was constructed not only by reflecting expert opinions but also by integrating quantitative data on injury occurrences by fishing operation process, as outlined in the compensation payment records (Table 8). This integration enhanced the reliability of the data. However, unknown processes, where the operation steps were unclear, were excluded from the analysis.

Table 8. Breakdown of injuries by fishing process. Unit: Cases (%).

Injury Type \ Process	Preparation for Sea	Sailing for Fishing	Fishing	Sailing for Landing	Unloading	Maintenance	Unknown Process	Total
Trip/Slip	21	40	307	19	16	17	91	511
Stuck	10	2	260	3	4	14	26	319
Bump/Hit	9	15	300	6	3	8	49	390
Falling from height	7	5	37	5	5	5	33	97
Crumble/Crushed	2	0	5	0	0	0	2	9
Unnatural posture	2	5	74	4	3	4	17	109
Exposure to extreme temperatures	0	1	2	0	0	7	6	16
Exposure to chemicals	0	3	33	0	0	10	10	56
Others	5	27	58	10	1	8	174	283
Total	56 (3.1)	98 (5.5)	1076 (60.1)	47 (2.6)	32 (1.8)	73 (4.1)	408 (22.8)	1790 (100.0)

Based on the findings, four high-risk injuries—Trip/Slip, Bump/Hit, Stuck, and Unnatural Posture—were identified, and the corresponding RRNs were calculated, as presented in Tables 9–12. As illustrated in Figure 1, most trap fishing vessels are classified as small vessels, measuring under 12 m in length. Therefore, the locations of injuries were categorized into three areas: the deck (with the fish hold located beneath the deck, included as part of the deck area), the engine room, and the wharf.

Table 9. Risk ranking number of Trip/Slip in fishing process.

Accident Subcategory	Preparation for Sea	Sailing for Fishing	Fishing	Sailing for Landing	Unloading	Maintenance
Deck	F3/S2(4)	F3/S2(4)	F2/S4(5)	F3/S2(4)	F3/S2(4)	F3/S1(3)
Engine room	F3/S1(3)	F3/S1(3)	F3/S1(3)	F3/S1(3)	-	F3/S2(4)
Wharf	F3/S2(4)	-	-	-	F3/S2(4)	F3/S1(3)

Table 10. Risk ranking number of Bump/Hit in fishing process.

Accident Subcategory	Preparation for Sea	Sailing for Fishing	Fishing	Sailing for Landing	Unloading	Maintenance
Deck	F3/S2(4)	F3/S1(3)	F3/S3(5)	F3/S1(3)	F2/S4(5)	F3/S1(3)
Engine room	F3/S2(4)	F3/S1(3)	F3/S1(3)	F3/S1(3)	-	F2/S4(5)
Wharf	F3/S1(3)	-	-	-	F3/S2(4)	F3/S1(3)

Table 11. Risk ranking number of Stuck in fishing process.

Accident Subcategory	Preparation for Sea	Sailing for Fishing	Fishing	Sailing for Landing	Unloading	Maintenance
Deck	F3/S1(3)	F3/S1(3)	F2/S4(5)	F3/S1(3)	F3/S2(4)	F2/S3(4)
Engine room	F2/S4(5)	F3/S1(3)	F3/S3(5)	F3/S1(3)	-	F2/S4(5)
Wharf	F3/S1(3)	-	-	-	F3/S2(4)	F3/S1(3)

Table 12. Risk ranking number of Unnatural Posture in fishing process.

Accident Subcategory	Preparation for Sea	Sailing for Fishing	Fishing	Sailing for Landing	Unloading	Maintenance
Deck	F3/S1(3)	F3/S1(3)	F2/S4(5)	F3/S1(3)	F3/S2(4)	F3/S2(4)
Engine room	F3/S2(4)	F3/S1(3)	F2/S3(4)	F3/S1(3)	-	F3/S2(4)
Wharf	F3/S1(3)	-	-	-	F3/S2(4)	F3/S1(3)

3.1.3. Equivalent Total

Based on the RRNs calculated from Tables 9–12, the risk levels of injuries by process and location were identified, and risk level categories were established, as shown in Table 13.

Table 13. Number of occurrences of each ranking score.

Risk Ranking Number	Number of Occurrences			
	Trip/Slip	Bump/Hit	Stuck	Unnatural Posture
3	6	8	7	7
4	7	3	3	6
5	1	3	4	1

Additionally, the equivalent total (ET) can be calculated using the RRN categories. A higher ET value indicates a relatively higher risk level. The ET is calculated based on the fact that the severity and frequency ranges in the Risk Matrix are generally close to a logarithmic scale [28]. For example, a risk level of 8 is treated as 10^4 if risk level 4 is used as the base. Therefore, using 4 as the base, the following calculations are made [15]:

$$\text{Trip/Slip: } 4 + \log(7 + 10) = 5.23$$

$$\text{Bump/Hit: } 4 + \log(3 + 30) = 5.52$$

$$\text{Stuck: } 4 + \log(3 + 40) = 5.63$$

$$\text{Unnatural posture: } 4 + \log(6 + 10) = 5.20$$

The quantitative data analysis revealed that the highest occurrence rates were observed for Trip/Slip, Bump/Hit, Stuck, and Unnatural Posture, in that order (Table 6). However, the RRN analysis indicated that the highest risk levels were associated with Stuck, followed by Bump/Hit, Trip/Slip, and Unnatural Posture. Based on these findings, the study focused on conducting a risk assessment for the Stuck injury.

3.2. Step 2. Risk Estimation

The primary objective of risk estimation is to clearly identify the causes and underlying factors contributing to the Stuck injury, which was determined to be the highest risk injury type in Step 1. As outlined in Section 2.1.3, it was assumed that most maritime accidents are caused by the human element. Thus, the human element was identified as the main cause of Stuck injuries. The six factors influencing the human element, as proposed by the IMO (People factors, Organization on board, Working and living conditions, Ship factors, Shore-side management, External influences, and environment), were selected as the primary indirect factors. Additionally, the sub-factors presented in Figure 3 were identified as secondary indirect factors. Using the FTA technique, the study performed a risk estimation to quantitatively analyze the relationship between accident patterns and their underlying factors.

3.2.1. Survey Results

The risk rankings of injuries, as perceived by field experts, differed slightly from those derived from the analysis of 1790 quantitative cases. However, they were largely consistent with the ET values calculated from the RRN. While there were minor differences based on years of work experience, experts generally ranked the frequency of injuries as follows: Stuck (42.2%), Bump/Hit (27.8%), Trip/Slip (16.7%), and Falls (12.3%) (Table 14).

Table 14. Survey results on injury types by years of experience. Unit: Number (%).

Injury Type \ Years of Experience	Less than 10 Years	10 to Less than 20 Years	20 to Less than 30 Years	30 Years or More	Total
Stuck	4 (66.7)	11 (57.9)	10 (38.5)	13 (34.2)	38 (42.2)
Bump/Hit	1 (16.7)	0 (0.0)	8 (30.8)	16 (42.1)	25 (27.8)
Trip/Slip	0 (0.0)	4 (21.1)	6 (23.1)	5 (13.2)	15 (16.7)
Fall	1 (16.7)	4 (21.1)	2 (7.7)	5 (13.2)	12 (13.3)
Total	6 (100.0)	19 (100.0)	26 (100.0)	38 (100.0)	90 (100.0)

Additionally, the survey results on the causes of injuries, similar to those presented in Table 14, are shown in Table 15. The secondary indirect factor most frequently cited as a fundamental cause of injuries was "fishing practices that do not prioritize safety" under the Organization on board category (11.7%), followed by "Personal negligence" under People factors (10.6%) and "Harsh natural conditions such as rough waves" under External influences and environment (8.9%).

Secondary indirect factors related to Organization on board received higher response rates than those under People factors, and secondary indirect factors under External influences and environment also garnered higher response rates compared to other categories. These findings suggest that a variety of indirect factors, extending beyond People factors alone, contribute to the human element in fishing vessel accidents.

Table 15. Survey results on secondary indirect factors. Unit: Number (%).

Primary Indirect Factor	Secondary Indirect Factor	Answer
People factors (C1)	Personal negligence (D11)	38 (10.6)
	Failure to wear personal protective equipment (D12)	7 (1.9)
	Incorrect working posture (D13)	16 (4.4)
	Unskilled fishing operations (D14)	10 (2.8)
Organization on board (C2)	Inappropriate fishing methods (D21)	2 (0.6)
	Poor communication due to mixed foreign fishermen (D22)	8 (2.2)
	Reduced concentration due to fatigue, such as lack of sleep (D23)	17 (4.7)
	Insufficient pre-education on risk factors/situations (D24)	25 (6.9)
	Fishing practices that do not prioritize safety (D25)	42 (11.7)

Table 15. *Cont.*

Primary Indirect Factor	Secondary Indirect Factor	Answer
Working and living conditions (C3)	Cluttered and untidy deck (D31)	6 (1.7)
	Confined working space with no place to escape (D32)	17 (4.7)
	Dangerous fishing gear with high tension (D33)	16 (4.4)
	Impaired communication due to severe noise and vibration (D34)	11 (3.1)
Ship factors (C4)	Structural defects in fishing machinery (D41)	21 (5.8)
	Lack of warning devices for abnormal operations (D42)	8 (2.2)
	Unsafe arrangement of fishing equipment (D43)	7 (1.9)
	Absence of emergency stop devices (D44)	19 (5.3)
	Aging equipment and poor maintenance (D45)	28 (7.8)
	Defective safety barriers such as no-entry barriers (D46)	7 (1.9)
Shore-side management (C5)	Lack of guidelines on work regulations (D51)	6 (1.7)
	Failure to post safety rules (D52)	5 (1.4)
	Absence of hazard warning signs (D53)	8 (2.2)
	Inadequate management of health examinations for workers (D54)	4(1.1)
External influences and environment (C6)	Harsh natural conditions such as rough waves (D61)	32 (8.9)
	Total	360 (100.0)

3.2.2. Construction of FT Diagram

In general, accidents are broadly categorized into those caused by human error and those resulting from natural disasters. Specifically, accidents can be classified as those caused by human actions and those triggered by unavoidable natural phenomena. However, since this study focuses on injuries attributable to the human element, only events related to human actions were considered.

The injury type "Stuck" was designated as A, with the human element identified as the direct cause, assigned as B. Additionally, as shown in Table 15, the six primary indirect factors influencing the human element were designated as C, and the secondary indirect factors (or basic factors) were designated as D (Figure 4).

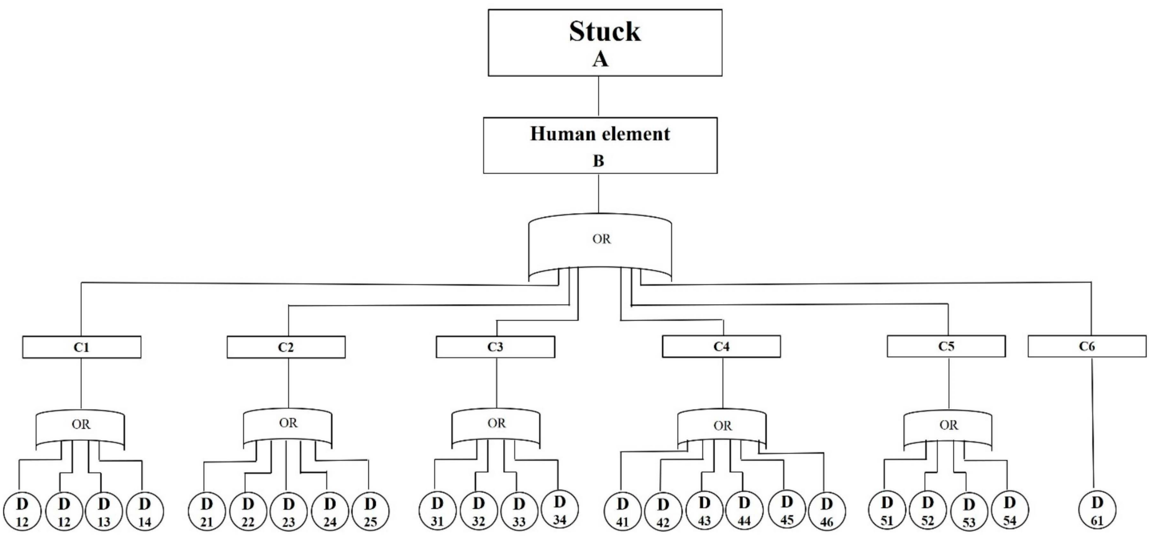


Figure 4. Fault tree diagram for the injury type Stuck.

3.2.3. FT Quantification and Risk Estimation

Using the survey results from Table 15, the occurrence rates of the secondary indirect factors were calculated and are presented in Table 16.

Table 16. Occurrence rates of secondary indirect factors. Unit: Number.

D11: 0.106	D12: 0.019	D13: 0.044	D14: 0.028		
D21: 0.006	D22: 0.022	D23: 0.047	D24: 0.069	D25: 0.117	
D31: 0.017	D32: 0.047	D33: 0.044	D34: 0.031		
D41: 0.058	D42: 0.022	D43: 0.019	D44: 0.053	D45: 0.078	D46: 0.019
D51: 0.017	D52: 0.014	D53: 0.022	D54: 0.011		
D61: 0.089					

Secondary indirect factors are fundamental factors embedded within primary indirect factors and can act as causes for the occurrence of primary factors.

Therefore, the occurrence rates of secondary indirect factors can be calculated using an OR gate (logical union), which determines the occurrence rates of the primary indirect factors as follows:

$$C1 = 1 - \{(1 - 0.106) * (1 - 0.019) * (1 - 0.044) * (1 - 0.028)\} = 0.18505(18.5\%)$$

$$C2 = 1 - \{(1 - 0.006) * (1 - 0.022) * (1 - 0.047) * (1 - 0.069) * (1 - 0.117)\} = 0.2384(23.8\%)$$

$$C3 = 1 - \{(1 - 0.017) * (1 - 0.047) * (1 - 0.044) * (1 - 0.031)\} = 0.13218(13.2\%)$$

$$C4 = 1 - \{(1 - 0.058) * (1 - 0.022) * (1 - 0.019) * (1 - 0.053) * (1 - 0.078) * (1 - 0.019)\} = 0.22588(22.6\%)$$

$$C5 = 1 - \{(1 - 0.017) * (1 - 0.014) * (1 - 0.022) * (1 - 0.011)\} = 0.06251(6.3\%)$$

$$C6 = 1 - (1 - 0.089) = 0.089(8.9\%)$$

Thus, the occurrence rates of the primary indirect factors influencing the direct cause, the human element, were found to be highest for Organization on board (23.8%), followed by Ship factors (22.6%), People factors (18.5%), Working and living conditions (13.2%), External influences and environment (8.9%), and Shore-side management (6.3%).

It is widely acknowledged that injuries in fishing operations are often caused by the human element, particularly Personal negligence, and that preventive measures have typically focused on uniform education and training. However, the results of this study revealed that Organization on board had a greater impact than People factors, with Ship factors also exerting a significant influence.

Furthermore, all primary indirect factors contribute to the human element as causal factors. Therefore, using an OR gate (logical union), the occurrence rate of the human element as the direct cause of Stuck was calculated as follows:

$$B = 1 - \{(1 - 0.185) * (1 - 0.238) * (1 - 0.132) * (1 - 0.226) * (1 - 0.063) * (1 - 0.089\} = 0.64385(64.4\%)$$

Thus, the probability of the human element occurring due to various indirect factors is 64.4%, indicating that its impact on the Stuck injury is substantial.

3.2.4. Validation of FTA Results

Based on the compensation payment data presented in Section 3.1.1 and the expert survey results in Section 3.2.1, the risk estimation results indicate that the probability of the human element occurring in trap fishing vessel operations is 64.4%. In contrast, for other fishing vessel accidents, such as collisions, the probability of occurrence due to human error (e.g., lack of vigilance) exceeds 70% [35], which supports the validity of the FTA conducted in this study. However, the validation of the FTA model itself, used in the risk estimation process, is also necessary. To achieve this, this study employed sensitivity analysis from various validation techniques (data validation, test validation, field trials, subsystem validation, and sensitivity analysis) [36]. Sensitivity analysis is well known as a preferred method in systems that rely on probability and uncertainty management [37].

In this study, the following two axioms were applied to verify the reliability of the FTA model [15].

Axiom 1: If there is a slight increase in the subjective prior probability of a basic event, the probability of the top event should relatively increase.

Axiom 2: If there is a slight decrease in the subjective prior probability of a basic event, the probability of the top event should decrease accordingly.

When the occurrence probability of the most frequent secondary indirect factor, "fishing practices that do not prioritize safety", was increased by 20%, the probability of the human element occurring rose from 64.4% to 65.4%, an increase of 1%. Conversely, when the probability was decreased by 20%, the probability of the human element occurring dropped by 0.9%, confirming that the model satisfied both axioms (Table 17).

Table 17. Validation of the fault tree analysis model. Unit: %.

Probability of Fishing Practices That Do Not Prioritize Safety	Probability of Human Element Occurrence
Original (11.7%)	64.4%
20% increase (14.04%)	65.4%
20% decrease (9.36%)	63.5%

3.3. Step 3. Risk Control Options (RCOs)

To perform the analysis in this section, it is essential to identify the basic events that have the greatest influence on the top event. Table 15 presents the occurrence probabilities for all secondary indirect factors (basic events), with the highest-ranked secondary indirect factor being "fishing practices that do not prioritize safety" (11.7%).

As discussed throughout this paper, maritime accidents in fishing operations are frequently attributed to human error, leading to the implementation of preventive measures primarily focused on crew safety training. However, the results of this study revealed that multiple underlying factors, beyond the human element, contribute to accidents. Therefore, prevention strategies that focus solely on fishermen's behavior are no longer the optimal solution. Instead, selective and multifaceted preventive measures should be implemented to enhance safety and operational efficiency.

In response to the identification of "fishing practices that do not prioritize safety" as the highest-ranked secondary indirect factor, the authors propose three RCOs:

Conducting Fishermen Training: In South Korea, the Korea Maritime and Fisheries Training Institute offers safety-related training programs for a fee [38]. This training, in accordance with Article 116 of the Seafarers Act, covers emergency response procedures, the use of lifesaving equipment, and measures to prevent safety accidents during vessel operations [39].

Developing Accident Management Manuals: The National Institute of Fisheries Science, a government-affiliated agency in South Korea, produces and distributes accident prevention manuals aimed at mitigating occupational injuries in fishing operations [21]. These manuals include checklists for each fishing process, emergency response guidelines, information on accident-prone operations, and measures to prevent such accidents. These materials can serve as a valuable resource for improving accident prevention.

Installing Safety Equipment: Trap fishing vessels use net hauling machines to retrieve traps, which poses a risk of entanglement. During this process, fishermen's hands or clothing can become caught in the lines coiled on the deck, potentially leading to serious injuries. To prevent such accidents, the installation of an emergency stop device is necessary. This device would allow the fishermen to immediately halt the machine's operation in case of an emergency. In 2020, the National Institute of Fisheries Science developed and patented an emergency wireless stop device that can be worn by fishermen, enabling them to stop the machine by pressing a button during emergencies. The patented device is known as the "Wearable Safety Device for fishing Vessel Crew" (Patent No. 10-226015, 2020.11) [40].

3.4. Step 4. Cost–Benefit Analysis (CBA)

Selected RCOs must be attractive in terms of cost-effectiveness, meaning that their benefits should outweigh the financial costs incurred during implementation. The IMO assumes an Implied Cost of Averting a Fatality (ICAF) value of £2,000,000 (about $2,500,000), which represents the typical value of human life used in maritime industry cost–benefit analyses [41]. However, in this study, the compensation payment data provided quantitative values, which were used for the cost–benefit assessment. The compensation paid for 319 cases of Stuck injuries over five years amounted to $8,607,606. Assuming that Stuck injuries are solely caused by the human element, the occurrence rate of the human element was treated as the occurrence rate of Stuck injuries. Accordingly, the 64.4% occurrence probability of the human element corresponds to $5,543,298 in compensation costs.

For the purpose of the cost–benefit calculation, it was assumed that implementing the three RCOs presented in Section 3.3 would reduce the occurrence rate of the secondary indirect factor, "fishing practices that do not prioritize safety", to zero. In this scenario, the occurrence probability of the human element would decrease to 59.7%, which corresponds to $5,141,745 in compensation costs. Therefore, if the occurrence rate of fishing practices that do not prioritize safety were reduced to zero, the probability of the human element occurrence would decrease from 64.4% to 59.7%, resulting in a reduction of $404,558 in compensation costs. This difference, equivalent to 4.7% of the total compensation paid for Stuck injuries ($8,607,606), was set as the cost–benefit effectiveness value in this study. As of 2020, there were a total of 1385 insured trap fishing vessels and 6179 insured fishermen. All cost–benefit analyses were adjusted based on these figures.

3.4.1. RCO1

According to the annual training plan of the Korea Maritime and Fisheries Training Institute, the cost of fishing vessel safety training is $53 per person (Figure 5). If all 6179 insured fishermen participated in the training, the total cost would be $327,487, resulting in a benefit of $77,071. Therefore, RCO1 is deemed effective (Table 18).

Table 18. Cost–benefit analysis of risk control option 1. Unit: USD.

Category	Amount
Cost–benefit effectiveness value	404,558
Cost of safety training	327,487
Benefit	77,071

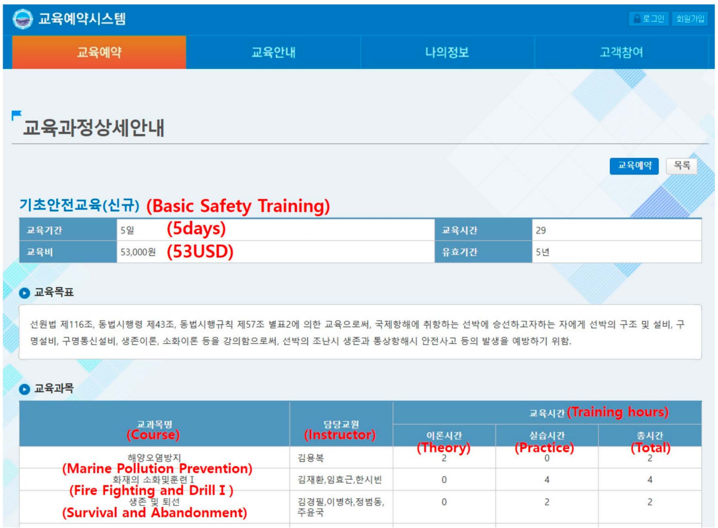


Figure 5. Details on safety training.

3.4.2. RCO2

The National Institute of Fisheries Science, a government agency in Korea, developed an "Accident Prevention Manual" to prevent injuries on fishing vessels (Figure 6). The total cost for its development, from research to production, was approximately $150,000. Assuming a printing cost of $15 per copy and distribution to all 6179 insured fishermen, the total cost would be $92,685, resulting in a benefit of $161,873. Therefore, RCO2 is deemed effective (Table 19).

Figure 6. Accident prevention manual for trap fishing operations.

Table 19. Cost–benefit analysis of risk control option 2. Unit: USD.

Category	Amount
Cost–benefit effectiveness value	404,558
Cost of accident prevention manual	150,000 + 92,685 = 242,685
Benefit	161,873

3.4.3. RCO3

Details related to the development of an emergency wireless stop device for quickly halting the net hauling machine during emergencies are shown in Figure 7. The installation cost per device was estimated at $1100. If all 1385 insured trap fishing vessels were equipped with this device, the total cost would be $1,523,500, resulting in a loss of $1,118,942. Therefore, RCO3 is considered ineffective (Table 20).

Based on the CBA results, RCO2 was determined to be the most effective option among the three proposed RCOs.

Figure 7. Details on the emergency stop device.

Table 20. Cost–benefit analysis of risk control option 3. Unit: USD.

Category	Amount
Cost–benefit effectiveness value	404,558
Cost of emergency stop device	1,523,500
Loss	1,118,942

3.5. Step 5. Decision-Making

Decision-making in this context involves selecting the most cost-effective risk control RCO by focusing on the most effective means of improving safety while also revisiting the evaluations conducted in Steps 1 through 4 [15]. Based on the results of Step 4, providing accident prevention manuals to fishermen was identified as the most financially efficient method for addressing the secondary indirect factor, "fishing practices that do not prioritize safety", which has the greatest impact on the occurrence of Stuck injuries.

The application of the Formal Safety Assessment (FSA) technique to analyze fishing vessel accidents represents a significant step forward in establishing systematic preventive measures for these incidents. This study demonstrated the applicability of the FSA in fishing vessel accident analysis and emphasized that reliable results can be derived if sufficient quantitative and qualitative data are available.

4. Discussion

4.1. Challenges in Applying Formal Safety Assessment to Fishing Vessel Accidents

Fishing vessels, due to their operational characteristics, typically carry a larger number of crew members, resulting in significantly higher rates of human casualties compared to merchant ships [1]. However, accidents involving fishing vessels rarely lead to severe marine pollution or financial losses; this contributes to a relative lack of quantitative data on such incidents [10]. This lack of databases has compelled researchers to rely on non-standardized analytical methodologies to devise preventive measures, often resulting in inconsistent findings [5,9] and delaying the development of generalized prevention strategies.

In this study, the application of the FSA technique demonstrated its capability to propose quantitative and objective preventive measures. Furthermore, the findings revealed that the continued occurrence of fishing vessel accidents and the absence of systematic prevention are not due to differences in vessel type or the nature of the accidents but are largely attributable to the lack of a comprehensive quantitative database [2]. Therefore, the establishment of an objective, centralized database on fishing vessel accidents would enable the application of standardized techniques like the FSA, facilitating the derivation of consistent and reliable results.

4.2. Effectiveness of the Formal Safety Assessment Technique

The FSA is a technique based on quantitative data [12,42]. However, given the limited availability of quantitative data on fishing vessel accidents, this study utilized fishermen's insurance compensation records, providing accessible year-by-year data. Additionally, expert surveys were conducted to supplement the analysis with qualitative data. The results confirmed that the full FSA process is effectively applicable to fishing vessel accident analysis, enabling the identification of critical risks and the proposal of targeted preventive measures.

A key contribution of this study is the cost–benefit analysis (CBA), which quantitatively evaluated the economic impacts of various preventive measures. As presented in Section 3.4, the three preventive measures currently in practice have not significantly reduced fishing vessel accidents, indicating relatively low cost-effectiveness [13]. However, the findings revealed that the RCO2 was the most effective preventive measure among the three. This quantitative approach not only enhances the credibility of the research but also facilitates decision making for stakeholders, including policymakers and industry leaders, while offering a cost-efficient solution.

4.3. Implications for Fishing Vessel Safety

While conventions such as SOLAS 1974 and MLC 2006 have established clear safety and welfare standards for merchant ships' crews [5], fishing vessels are subject to fewer and less comprehensive international regulations [43]. This regulatory gap makes it more difficult to improve safety in the fishing industry.

Moreover, as mentioned in the introduction, even international organizations like the IMO and ILO are unable to accurately estimate the number of fatalities caused by fishing vessel accidents, with reports indicating that over 32,000 fatalities occur annually on fishing vessels [1].

In this context, this study demonstrated the applicability of the FSA technique to fishing vessel accidents, providing a foundation for future research aimed at standardizing fishing vessel accident analysis. Unlike previous studies using non-standardized methods, this research is significant for its use of the official technique suggested by the IMO, which offers a quantitative assessment. Additionally, by proposing systematic and cost–benefitoriented preventive measures, this study marks a significant advancement in the prevention of fishing vessel accidents.

4.4. Future Research Direction

This study has limitations, focusing on trap boats operating in South Korea and utilizing data from insurance compensation records. Future research should incorporate accident data from various countries and fishery types, along with development of international data collection and standardized recording procedures for more accurate assessment of causes and outcomes. This will provide a foundation for a more comprehensive evaluation of the impact of the FSA technique on fishing vessel safety.

Furthermore, the FSA technique, developed for merchant vessels, was applied to fishing vessels without modification in this study. However, considering the specific operating characteristics of fishing vessels, some aspects may not be suitable, and these will be revised through continuous monitoring to ensure proper application.

5. Conclusions

The FSA technique proposed by the IMO is a systematic methodology for preventing maritime accidents. However, its application to fishing vessel accident analysis faces significant challenges due to the scarcity of sufficient quantitative data on such incidents. Despite this limitation, the authors believe that studies on fishing vessel accidents should be conducted using standardized analytical methodologies. Accordingly, the FSA process was implemented using fishermen's insurance compensation data, which facilitated a quantitative analysis of costs and accident types.

While the study was conducted with limited data from a single industry, it successfully analyzed fishing vessel injuries both quantitatively and qualitatively. Furthermore, the cost–benefit results were quantified, enabling the proposal of selective and effective preventive measures. In conclusion, the FSA technique is considered highly applicable to the analysis of injuries occurring on fishing vessels, provided that sufficient quantitative data are available.

It is hoped that the procedures followed in this study will serve as a reference for establishing formal methodologies for analyzing fishing vessel accidents and that the findings will contribute to the prevention of injuries among fishermen worldwide.

Author Contributions: Conceptualization, S.-H.K.; methodology, K.-J.R.; software, S.-H.L.; analysis, S.-H.K.; writing—original draft preparation, Y.-W.L.; writing—reviewing and editing, Y.-W.L.; supervision, S.-H.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was conducted as part of the "Development and demonstration of data platform for AI-based safe fishing vessel design (RS-2022-KS221571)" of the Ministry of Oceans and Fisheries.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used to support the findings of this study are available from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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