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Application of Rough Set Theory and Bow-Tie Analysis to Maritime Safety Analysis Management: A Case Study of Taiwan Ship Collision Incidents

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Featured Application: The integrated method used in this study can be extended to risk analysis and management of various hazards, including those associated with lack of statistical information, regional specificity, and multiple risk factors.

Abstract: The surrounding waters of Taiwan are evaluated as a moderate risk environment by Casualty Return, Lloyd's Registry of Shipping. Among all types of maritime accidents, ship collisions occur most often, which has severe consequences, including ship damage, sinking and death of crews, and destruction of marine environments. It is, therefore, imperative to mitigate the risk of ship collision by exploring the risk factors and then providing preventive measures. This study invited domain experts to form a decision-making group, which helped with the risk assessment. The initial set of risk factors was selected from the literature. The expert group then identified seven representative risk factors using rough set theory (RST). The researchers worked with the experts to delineate the diagram of a bow-tie analysis (BTA), which provided the causes, consequences, and preventive and mitigation measures for ship collision incidents. The results show an integrated research framework for the risk assessment of ship collision that can effectively identify key factors and associated managerial strategies to improve navigation safety, leading to a sound marine environment.

Keywords: group decision making; risk assessment; maritime data analysis; ship collision

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1. Introduction

1.1. Background

Taiwan is an island country surrounded by sea and relies highly on air and sea transportation for foreign traffic and trade. Considering 2019 as an example, the loading and unloading freight through domestic, international, cross-strait route, and re-export flights across all airports in Taiwan reached 2.315 million metric tons [1]. As for shipping, the loading and unloading freight through domestic ports and international commercial ports amounted to 734.64 million metric tons. This accounted for 99.69% of all cargo transportation in 2019. Obviously, sea transportation plays an important role in economic and trade development in Taiwan.

Located at the pivot of Asia, the surrounding waters of Taiwan will inevitably see an increase in the number of incidences of collisions and other maritime accidents due to the complexity of maritime traffic flows and traffic density under the premise of constant and limited sea routes [2]. For example, ship collisions between merchant ships and inshore fishing

boats sometimes occur. According to "Casualty Return" from Lloyd's Registry of Shipping, that assessed the risk of marine environments on the basis of the rate of incidents, traffic density, complexity of traffic flow, visibility, variation of tides, currents, etc., the surrounding waters in Taiwan are evaluated as a moderate risk environment. The count of maritime incidents of various types in Taiwan was 2105 from 2011 to 2020, of which 1643 incidents, or 78.05% of all incidents, occurred in the surrounding waters of Taiwan. They resulted in 177 people injured, 133 missing, 181 dead, 962 ships damaged, and 41 ships sunk [3].

Most maritime accidents not only influence social and economic aspects but also involve personnel safety and even cause irreversible damage to marine environments [4,5]. For example, a ship collision would result in damage to the ship and sunken ships in conjunction with personal injury, missing persons, and even death [6–8]. It is, therefore, imperative to mitigate the risk of maritime accidents by exploring the risk factors and then providing preventive measures.

Maritime accidents are categorized into eight categories by the IMO, including foundering, missing, fire/explosion, collision, contact, grounding, heavy weather/ice damage, and hull/machinery. On the basis of the definition of the IMO and consideration of Taiwanese national affairs, maritime accidents were defined by the Central Disaster Prevention and Response Council in 2019 in Taiwan as malfunction, foundering, grounding, collision, fire, explosion, and other accidents related to the ship, cargo, crew, or passengers. Among all, ship collisions are the main cause of maritime accidents, which encompasses the incidents between two ships and between ships and other objects [9]. In addition, the ships include not only merchant ships but also fishing boats, traffic boats, and recreational fishing boats. The total number of ship collisions was 559 from 2011 to 2020, indicating a high frequency of incident occurring rate, with an average of one ship collision every 6.5 days.

1.2. Risk Assessment

The International Maritime Organization (IMO) formulated a formal safety assessment (FSA) to prevent and reduce the occurrence of maritime accidents and to improve the safety of ships and maritime navigation [10–12]. The FSA includes hazard identification, risk assessment, risk control options, cost benefit assessment, and recommendations for decision making. In a risk assessment, the FSA uses mainly quantitative methods as risk assessment tools, such as using a Bayesian network to calculate the incidence rate, or a semi-empirical risk management analysis model [13], such as fault tree analysis (FTA) [14–16] and event tree analysis (ETA) [17,18]. However, the aforementioned methods may have some pitfalls, such as ambiguous outcomes when two experts have totally opposite opinions on the same subject. Therefore, proposing a meaningful research approach to improve FSA is of paramount importance for the successful application of supportive maritime safety policy-making instruments [19].

The occurrence of maritime accidents is normally caused by multiple factors and complicated processes rather than just one single factor [17,20,21]. The analytical aspects concerning preventative factors of ship collision accidents focus mainly on the risk factors of humans [11,22–28], the ship or management [2,28,29], and the navigation and natural environments. A majority of the previous research explored the hazard assessments of post ship collision accidents; however, the simultaneous examination of the risk factors for ship collisions and the preventative and mitigation measures of a hazard assessment is limited. Therefore, a comprehensive evaluation of all three aforementioned aspects is needed.

Two potential approaches, including rough set theory (RST) and bow-tie analysis (BTA), can be integrated to form a comprehensive risk assessment framework. RST is a decision analysis tool aimed at extracting information and relevance from imprecise, incomplete, and uncertain data or human thoughts. This method is commonly used in medicine [30,31], transportation [32], finance [33], risk management [34], and decision analysis [35]. BTA is a qualitative analysis technique that integrates the FTA and the ETA [36] and focuses on the relationship between risk factors and incidents. This analysis conducts a comprehensive risk assessment and helps junior management or executive

managers to further achieve the highest standards of safety. Recently, BTA has been widely used in risk assessment analysis in various fields, such as medical safety [37,38], petrochemical engineering safety [39,40], marine risk management [41], traffic safety [42], and aviation technical safety [43].

1.3. Research Objective

In Taiwan, not every ship collision incident has a detailed record of the cause of occurrence, and maritime investigation reports are based on qualitative explanations. In addition, the related research on ship collisions focused on a single behavior or a research method for studying ship collisions from past studies [44–46]. Therefore, the study combined the qualitative characteristics of RST and the comprehensive characteristics of BTA through group decision making to conduct a risk assessment of ship collisions. It is expected that the risks of ship collision accidents can be evaluated more comprehensively to reduce the rate of incidents and damage in a local marine traffic environment such as Taiwan.

2. Methodologies

The authors collected the human, ship, and environment-related risk factors of ship collision incidents from native and foreign literature. After forming a decision-making group, we adopted a group decision-making and RST model to extract the representative risk factors of ship collision incidents. Finally, we used a bow-tie analysis to visualize the cause and possible consequences of ship collision accidents, as well as preventative and mitigation measures. A flow diagram is shown in Figure 1.

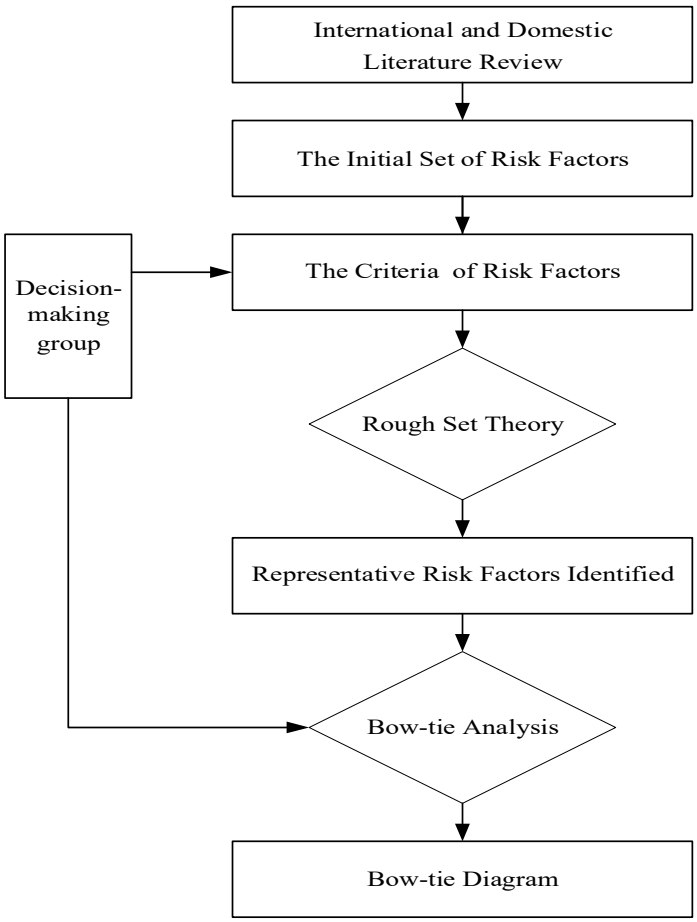


Figure 1. Flow diagram of the research.

2.1. Establishment of the Decision-Making Group

The decision-making group consisted of three captains and three experts to explore the risk factors of ship collisions. The decision-making group's background is summarized in Table 1.

Table 1. Decision-making group.

No.	Position	Education	Professional Field	Maritime Experience in Years
1	Captain of fishing boat	Senior high school	Navigation and management	38
2	Captain of fishing boat	Senior high school	Navigation and management	35
3	Captain of merchant ship	Master's degree	Navigation and management	31
4	Professor	Doctorate	Safety management	20
5	Pilot	Master's degree	Navigation and navigation safety	30
6	Manager	Bachelor's degree	Management	16

2.2. The Initial Set of Risk Factors

The authors performed a literature review of ship collision incidents and summarized 29 risk factors on the basis of three categories: human-made factors, ships, and environment. Among all, the human-made category included 15 factors, such as physical illness, absent-mindedness on duty, alcoholism, drugs, improper operation, and false personal judgment. Risk factors, such as unscheduled maintenance, insufficient equipment, mechanical failure, and old ship, were included in the ship category. Other factors, such as poor sea condition, dense fog, heavy rain, narrow channel, and excessive traffic density, were incorporated into the environmental category. The 29 summarized initial risk factors in this study are shown in Table 2.

Table 2. Summary of the initial risk factors for ship collisions.

Category	Factors	References
A: Human-made	A1: Personal physical illness	[2,17]
	A2: Absence-mindedness	[2,17,22–24,47,48]
	A3: Personal alcohol and drug habits	[17,25,26]
	A4: Stressed and nervous	[22,25,49–51]
	A5: Carelessness	[17,52]
	A6: Personal improper operation	[17,22,49,53]
	A7: Personal misjudgments	[26,50,53]
	A8: Unfamiliarity with local navigation rules	[49,53]
	A9: Unfamiliarity with COLREGS	[26,51,52]
	A10: Unwillingness to avoidance	[11,49,51,53]
	A11: Insufficient avoidance skills	[49,50]
	A12: Violation of regulations on duty	[11,17,52,53]
	A13: Incompatible communication of avoidance	[17,52,53]
	A14: Unfamiliarity of ship characteristics	[24,25,29,51]
	A15: Inaccurate maintenance	[25,49,54]
B: Ship	B1: Irregular maintenance	[25,49,54]
	B2: Insufficient equipment	[26,52,54]
	B3: Mechanical malfunction	[26,49]
	B4: Old ship	[11,49,53]
	B5: Ship characteristics	[17,22,25,26,47,48]
	B6: Cargo overloaded	[25,55]
	B7: Poor working environment	[11,25,53]
	B8: Local port management	[17,49]
	B9: Crew/labor shortage	[26,52]
C: Environment	C1: Poor sea conditions	[23,50]
	C2: Sudden changes of weather	[23,25]
	C3: Dense fog and heavy rain	[17,52,56]
	C4: Narrow channel	[17,23,57]
	C5: Traffic density	[10,23,25,52]

2.3. Explore the Risk Factor Criteria

After the decision-making group was established, the primary task was to develop the selection criteria for the risk factors of ship collision incidents to locate representative risk factors for further analyses. Thus, the study adopted a 3-point rating scale to achieve high levels of consistency in the decision-making group. The risk factor selection criteria are elaborated in Table 3.

Table 3. Description of the risk factor selection criteria.

Risk Factor	Description
Relevance	The measurement scales were divided into high relevance (H), medium relevance (M), and low relevance (L), which were based on the correlations between risk factors and ship collisions.
Influence level	The level of influence between risk factors and the ship collision incident was used mainly to measure the severity of the consequences of the ship collision. The factor with a higher degree of influence level would lead to a larger impact on a ship collision. The measurement scale included high influence (H), medium influence (M), and low influence (L).
Incidence rate	To effectively prevent the occurrence of ship collisions, the incidence rate of risk factors can accurately determine the incidence rate of ship collisions. The measurement scales were divided into high incidence rate (H), medium incidence rate (M), and low incidence rate (L).
Representativeness	The causes of ship collisions included human-made, ship, and environmental aspects, and the relevance, degree of influence, and incidence of each risk factor were also different. Therefore, the selection of risk factors should be examined for whether they were representative enough. The measurement scale was classified as high representativeness (H), medium representativeness (M), and low representativeness (L).

After determining the selection criteria, the members of the decision-making team measured the risk factors on the basis of the relevance, influence level, incidence rate, and representatives of each risk factor. On this stage, the members of the decision-making group held several meetings to discuss the representative risk factors based on the results of the selected criteria and, finally, came to a consensus. The measurement used a qualitative analysis instead of a quantitative analysis to avoid the occurrence of extremely opposite measurements among the decision-making team's members. The results of the decision-making team's consensus are shown in Table 4.

Table 4. The results of the decision-making team's consensus.

No.	Factors	Relevance	Influence Level	Incidence Rate	Representativeness
1	A1	L	L	M	M
2	A2	M	M	H	M
3	A3	H	M	M	M
4	A4	M	M	M	M
5	A5	H	H	H	H
6	A6	H	H	H	H
7	A7	M	H	H	M
8	A8	H	H	H	H
9	A9	H	M	H	M
10	A10	H	H	M	M
11	A11	M	M	H	H
12	A12	H	H	M	M
13	A13	H	M	H	H
14	A14	H	H	H	H
15	A15	M	M	H	M
16	B1	M	M	H	H
17	B2	M	H	H	M
18	B3	H	H	H	H
19	B4	H	L	M	M

Table 4. *Cont.*

No.	Factors	Relevance	Influence Level	Incidence Rate	Representativeness
20	B5	H	M	M	M
21	B6	M	H	H	H
22	B7	L	M	L	L
23	B8	M	M	M	M
24	B9	H	H	M	M
25	C1	H	H	H	H
26	C2	H	M	H	M
27	C3	M	M	H	H
28	C4	M	M	H	H
29	C5	H	H	H	H

2.4. Rough Set Theory (RST)

The RST was proposed by Pawlak, a Polish scholar, in 1982 [58]. RST is a decision analysis tool for dealing with uncertainty problems, and including the measurement of the uncertainty of a concept is an important issue in theory [59]. This study was based on the knowledge and experience of local experts. Therefore, we applied the theoretical basis of RST to analyze the special regional characteristics of the surrounding waters in Taiwan.

The basic concept of RST is to solve an ambiguous relationship in an information system (IS) that includes a finite set of objects, U, and a set of attributes, A, which can be expressed as IS = (U, A). RST determines the final decision rules through the distinction principle among lower/upper approximations and boundary, independence of attributes and core, and reduction of attribute values.

However, when considering the preference order of attribute criteria, RST cannot handle inconsistency problems that violate the dominance principle. Multicriteria decision analysis was redesigned to extract representative factors, which was expressed as $S = \langle U, Q, V, f \rangle$, where

U is a finite set of objects;

Q is a set of evaluation criteria, that is, a set of attributes $Q = \{q_1, q_2, \ldots, q_m\}$;

V is the set of all function values $= \bigcup_{q \in Q} V_q$, where V_q is the domain of the attribute;

f is the function value corresponding to the evaluation criterion.

$$f : \mathrm{U} \times \mathrm{Q} \to V,\ f(x,q) \in V_q,\ q \in Q,\ x \in U$$

The indiscernibility relation is represented as P, and the subset of the indiscernibility in the set U is represented as I_p, which is defined as

$$I_p = \left\{ (x,y) \in U \times U : f(x,q) = f(y,q) \forall_q \in P \right\}$$

That is, when (x, y) $\in I_p$, where x and y are the solutions that are difficult to identify in the relationship. U | I_p is the classification set of the different factor selection criteria in set U based on the different factors generated by I_p.

We classified indiscernible subsets after completing the basic data table of RST. The classification criteria were defined by the concepts of the lower bound approximation, $\underline{P}$, and the upper bound approximation, P.

$\underline{P}[X]$ is referred to as lower approximation, which means that the factor classification in I_p completely conforms to the criterion X, representing deterministic information.

$$\underline{P}[X] = \left\{ x \in U : I_p(x) \subseteq X \right\}$$

$P[X]$ is referred to as upper approximation, which means that the factor classification in I_p partially conforms to the criterion X, representing information with uncertainty.

$$P[X] = \bigcup_{x \in X} I_p(X)$$

$Bn_p(X)$ represents the boundary, meaning that it belongs to neither the X subset nor the non-X subset. When $\underline{P}$ is not equal to X, then X is the boundary expressed as follows:

$$Bn_p(X) = P[X] - \underline{P}[X]. \quad (1)$$

The Rough Sets Data Explorer (ROSE2) version 2.2 is a popular software that was developed by the Laboratory of Intelligent Decision Support Systems of Poznan University of Technology. ROSE2 has been used in various fields, such as medicine, transportation, land development, energy, tourism, and financial services, and has shown good performance in data decision analysis. For example, Lin et al., established an emergency medical triage system to reduce medical costs and improve health care quality with the help of ROSE2 [60]. Shiau and Huang proposed transportation strategies with elderly-friendly transportation indicators [61]. Zolin et al., established a sustainable land development system in rural and mountain areas [62]. Therefore, we applied it to analyze the risk factors of ship collision and derive decision rules.

2.5. Bow-Tie Analysis (BTA)

BTA is a management method and presents the results of risk analysis graphically. It was first used by Royal Dutch/Shell Group to execute risk management around the world [63]. Through BTA, the causes and consequences of an incident and related prevention and mitigation measures can be identified. Moreover, BTA is valuable and transparent, which would greatly enhance the risk awareness of managers and stakeholders and further the understanding of the importance of risk management [64,65].

BowTieXP version 10.2 is a software based on the theoretical foundation of BTA. It is used in various risk assessments, including in medicine, environment and disasters, energy, marine policy, water resources, and engineering safety analysis. The visualization of a BTA on risk management could effectively determine and solve risk factors and achieve higher safety measures, such as the marine ecosystem risk framework constructed by Cormier et al. [66] and the risk assessment of deep-sea mining conducted by Cormier and Londsdale [67].

We applied the software BowTieXP for the establishment of a risk diagram of a ship collision. The risks of a ship collision, preventive strategies, and consequences were visualized. As shown in the risk diagram, the event is shown in the middle column, and the causes of the event are shown to the left side of the diagram. The preventive management measures are shown between the events and the causes. The consequences of the events are presented on the right side of the diagram, and the mitigation management measures are shown between the event and the consequences.

3. Results

3.1. Representative Risk Factors

On the basis of the expert opinion and literature review, the following factor criteria were formed, including relevance, influence level, incidence rate, and representativeness. Subsequently, the members of the decision-making group discussed and analyzed the initial risk factors on the basis of the selection criteria and, finally, reached a consensus for the final measurements.

In the risk factors analysis of a ship collision, the relevance was represented by $RF1$, the influence level was represented by $RF2$, the incidence rate was represented by $RF3$, and the representativeness was $RF4$. We selected mainly the risk factors with high representativeness, so the set and inference were as follows:

$U = \{1, 2, 3, \ldots\ldots, n\}, n = 1 \sim 29$
$Q = \{RF1, RF2, RF3, RF4\}$
$RF1 = \{H, M, L\}$
$RF2 = \{H, M, L\}$
$RF3 = \{H, M, L\}$
$RF4 = \{H, M, L\}$

Then, we created a decision table based on Table 4 data and imported it into ROSE2. After calculation and analysis of rules induction and optimization by ROSE2, there were five decision rules, comprising three decision rules (i.e., RF4 = L, RF4 = M, and RF4 = H) and two approximate rules (i.e., RF4 = M and RF4 = H). The calculated results are shown in Table 5.

Table 5. The calculated results by ROSE2.

	RF1	RF2	RF3	RF4	Corresponding Risk Factors
Rule 1			L	L	22
Rule 2			M	M	1, 3, 4, 10, 12, 19, 20, 23, 24
Rule 3	H	H	H	H	5, 6, 8, 14, 18, 25, 29
Rule 4	M		H	M	2, 7, 15, 17
				H	11, 16, 21, 27, 28
Rule 5		M	H	M	2, 9, 15, 26
				H	11, 13, 16, 27, 28

We selected the highly representative risk factors, Decision Rule 3: RF1 = H and RF2 = H and RF3 = H, then RF4 = H, to obtain a comprehensive and effective risk assessment. The risk factors with high relevance, high influence level, and high incidence rate included carelessness, personal improper operation, unfamiliarity with local navigation regulations, unfamiliarity of ship characteristics, mechanical malfunction, poor weather condition, and traffic density.

- Carelessness

Carelessness is the main cause of ship collisions and other maritime accidents because of the weak safety awareness. Carelessness among a crew can take various forms, including failing to detect obstacles ahead and neglecting to adjust course or speed in a timely manner while operating the vessel. In addition, weak safety awareness can be a contributing factor, such as relying solely on past successful experiences and disregarding essential collision avoidance procedures [6,22,68].

- Personal improper operation

When a ship is sailing, it can use radio broadcasts or whistles to warn other ships. Additionally, the ship's engine or rudder can be used to adopt avoidance procedures to prevent collision events. However, sometimes ship collisions may occur due to improper operations by the crew sailing on duty, such as the wrong engine orders and rudder orders. In addition, ship collision may also occur when the helm chief operates incorrectly, such as operating starboard into port [6,68,69].

- Unfamiliarity of local navigation regulations

There are seven international commercial ports in Taiwan, and each commercial port has its own navigation regulations for the main channel and the meaning of the signal board. In addition, the anchoring area and the traffic separation scheme (TSS) have different regulations due to the local sea conditions. Furthermore, it is difficult to ensure that the crew on the ships have sufficient knowledge of local navigation regulations since various types of ships pass through the ports, including work ships, ferries, sightseeing transportation ships, and fishing ships. In particular, fishing boats have neglected the TSS regulations for fishing operations. Therefore, collisions between two ships occur frequently, as well as collisions between ships and other facilities [6,68,69].

- Unfamiliarity of ship characteristics

There are many types of ships, such as container ships, general cargo ships, bulk carriers, oil tankers, work ships, ferries, sightseeing boats, and fishing boats, and the characteristics of the vessels are different due to their purposes. Moreover, even the same type

of ship has a different floatability, stability, wave resistance, speed, and controllability due to the fact of different manufacturers, engines, and size design. Therefore, the unfamiliarity of a ship's characteristics could cause the speed and direction of a ship to become out of control when the ship is in an emergency [22,47,68].

- Mechanical malfunction

When a ship is facing a collision, various avoidance-related procedures can be adopted, such as radio broadcasting, whistles, flash warnings, or the use of operating engines and steering techniques [6,68,70].

- Poor sea conditions

Taiwan is in the subtropical monsoon zone, causing huge differences in the sea conditions around Taiwan. The transition from spring to summer usually occurs after the rainy season in April. As the southwest monsoon prevails and typhoons are formed in June, sea conditions become worse, accompanied by hundreds of kilometers of stormy areas and more than 6 m wave heights. Poor sea conditions can affect the radar display and easily cause a misjudgment. During the transition from autumn to winter in October, the northeast monsoon gradually strengthens, with an average wave height of 2 m. Although it is not as drastic as the typhoons in summer, it is still a high-occurrence season for ship collisions [68,70].

- Traffic density

Export-oriented global trade in Taiwan depends mainly on shipping, and coastal residents also rely on fishing for their livelihoods. At the same time, maritime tourism and recreation has flourished, resulting in large numbers of ships sailing around Taiwan and causing the surrounding waters to become hotspots of ship collisions. Various types were included, such as container ships, bulk-cargo ships, oil tankers, sightseeing ships, fishing boats, and official ships [68,70].

3.2. Bow-Tie Risk Analysis

We used the highly representative risk factors of ship collision incidents selected by RST and the decision-making group to analyze and discuss the preventive measures, possible consequences, and mitigation measures for each risk factor of ship collision incidents. Finally, the results were applied to BowTieXP to construct a complete bow-tie risk analysis chart for ship collision incidents. The result shows preventive management against ship collision incidents, as well as the mitigation measures after incidents to avoid more severe consequences (Figure 2).

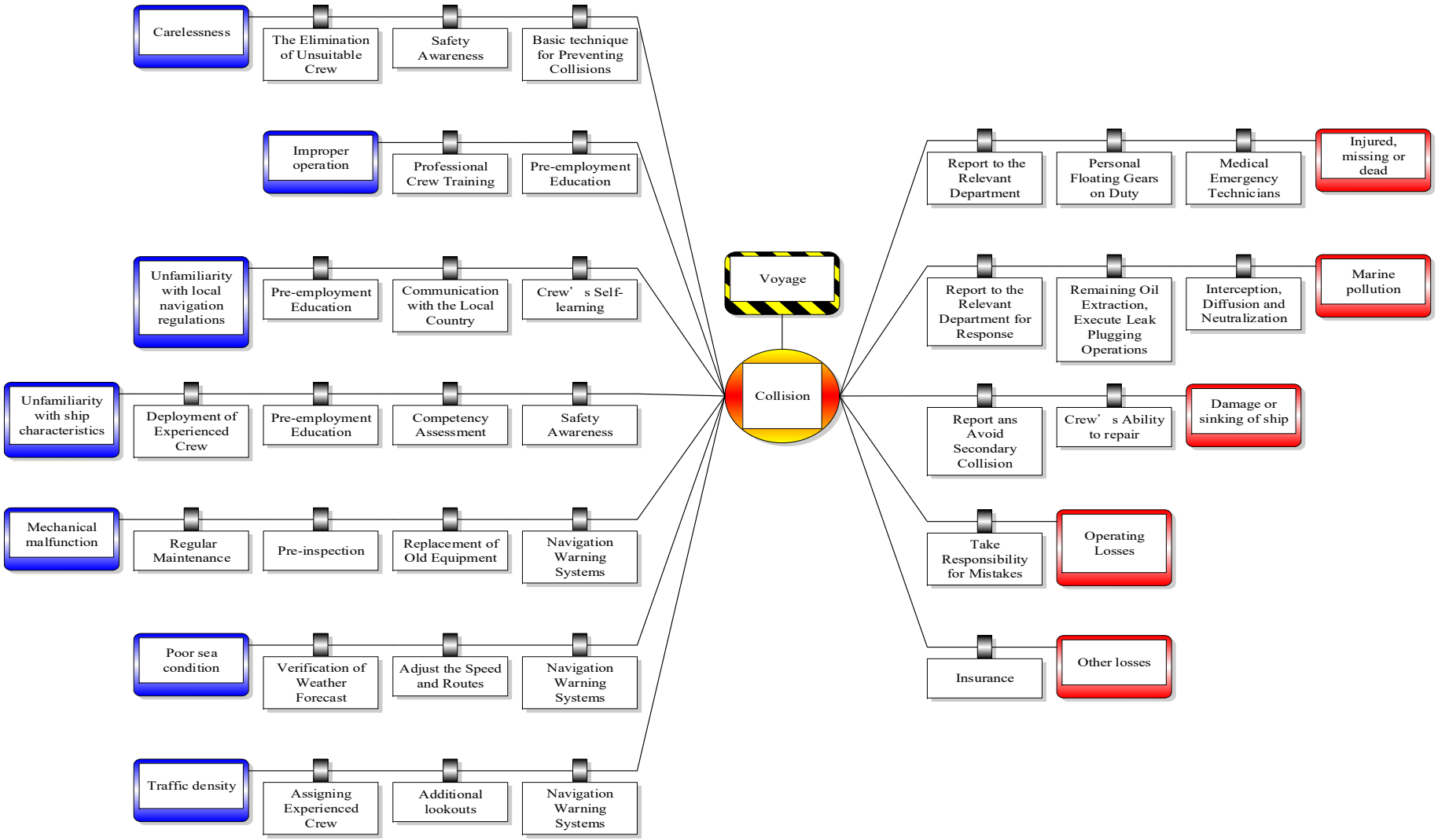


Figure 2. Bow-tie risk analysis diagram of ship collision incidents.

Seven factors of ship collisions were included, i.e., carelessness, improper operation, unfamiliarity with local navigation regulations, unfamiliarity with ship characteristics, mechanical malfunction, poor sea conditions, and traffic density. Moreover, the preventive measures were as follows:

- Carelessness

The preventive measures for carelessness included the elimination of unsuitable crew members and the establishment of basic techniques for preventing collisions and for safety awareness.

- Personal improper operation

The preventive measures for the improper operation of equipment included professional training, pre-employment education, training for crew members, and the set-up of a remote monitoring system.

- Unfamiliarity with local navigation regulations

The preventive measures for unfamiliarity with local navigation regulations included pre-employment education and training, communication with the local country, and establishment of a crew's self-learning attitude.

- Unfamiliarity with ship characteristics

The preventive measures for unfamiliarity with a ship's characteristics included the deployment of experienced crew members, pre-employment education and training, competency assessment, and the establishment of safety awareness.

- Mechanical malfunction

The preventive measures for mechanical malfunction, such as for an abnormality of the main engine, reducer, and steering gear, included regular maintenance, pre-inspection, replacement of old equipment, and the set-up of a remote monitoring system or intelligent navigation warning system.

- Poor sea conditions

The preventive measures for poor sea conditions included the verification of weather forecast data in the sailing plan and the use of intelligent navigation warning systems to adjust the speed and routes in time.

- Traffic density

The preventive measures for traffic density included assigning experienced crew to assist in operating the ship, increasing the crew for a sharp lookout, and setting-up a remote monitoring system or intelligent navigation warning system.

The consequences of ship collision, including crew casualties, marine pollution, damage or sinking of the ship and operating losses, etc. The relevant mitigation measures are described as follows:

- Injured, missing, or dead

Crews working on the outer deck on duty should wear buoys equipped with signal transmitters, and medical emergency technicians should be on board to rescue injured persons immediately. Moreover, the crew should immediately report to the relevant department for assistance when a person falls into the sea or disappears [6,7].

- Marine pollution

The condition of the ship should be checked at once when it collides. If there is a risk of oil pollution, the relevant local department should be notified immediately. The ship or rescue ship should carry out the residual oil extraction procedure, install oil pollution diffusion equipment, and execute leak plugging operations. Furthermore, they should take interception, diffusion, and neutralization measures to avoid serious marine pollution and ecological catastrophes [8]. The coast guard authority shall perform interdiction, collection of evidence, or enforcement referral tasks implemented pursuant to Marine Pollution Control Act in Taiwan, rather than the related procedures according to international convention.

- Damage or sinking of ships

The crew should immediately notify the local navigation department and inform other ships nearby to avoid secondary collisions and enlarging the damage. In addition, the crew should have the technical ability to repair ships and the problem-solving skills to prevent accelerating damage or sinking [6,71].

- Operating Losses

In addition to reporting to the local navigation department, the crew should report to the company right away. The company should immediately take responsibility for related mistakes and execute damage control to avoid ship detention and high fines affecting company losses and reputation damage [72,73].

- Other losses

In addition to damage to the ship, the cargo on board may fall into the sea or be damaged due to the strong collision. The captain and shipowner should be responsible for neglect in the navigation. Consider a fishing vessel collision as an example. A collision might cause the loss of a catch or damage to the refrigerating equipment, which would result in economic losses [6,72].

4. Discussion

In this study, we demonstrated two major advancements. First, we established a qualitative group decision model to determine the representative risk factors and further used BTA to decide on the causes of ship collision incidents and preventative and mitigation measures. Secondly, through the visualization of the risk factors with a bow-tie diagram, we shed light on the causes of the ship collisions more clearly. Such information can provide a comprehensive assessment for the decision-making departments, which includes public and private department. Considering Taiwan as an example, the public department includes the Ministry of Transportation and Communications, Fisheries Agency and Coast Guard; the private department includes sea freight forwarder and fishing associations. To achieve ship collision risk control more efficiently and reduce the incidence of ship collision incidents, this integrated analysis method can effectively improve the analysis results and risk control of ship collisions. In particular, this study is different from previous studies, which typically focus only on a single behavior and vessel. In fact, it can be used to explore the comprehensive risk assessment of ship collisions with multiple types of ships.

This study aimed to explore the representative risk factors of ship collisions, so the prevention and mitigation measures related to ship collision incidents focused mainly on the ship and its management company [22,47,48,74]. In addition, the decision-making group also proposed relevant management policies for each representative risk factor. For example, to prevent ship collision incidents due to the fact of personal carelessness or errors, the automatic ship collision avoidance system was proposed by the decision-making group to reduce the occurrence of ship collisions [75,76]. They also suggested the revision and strict enforcement of the penalty in the Shipping Law to effectively alert substandard ships. For high-risk vessels, they recommended the inspection of ships to execute Port State Control (PSC), including strict inspections and compulsory punishments [77]. The definition of a substandard ship is a ship whose hull, machinery, equipment, or operational safety is substantially below the standards required by the relevant convention or whose crew is not in conformance with the safe manning document [78]. The conditions for blacklisting ships are different for each country. In Taiwan, the blacklist of ships includes blacklisted ships under the Paris MoU [79] and Tokyo MoU [80], as well as ships engaged in illegal activities. Thus, PSC considers different inspection items for substandard ships and blacklisted ships. Although PSC is used to inspect foreign ships in national ports, if the ships that collide belong to local national ships, especially fishing boats, PSC is not applicable, and the relevant local national laws are enforced instead. The penalty provisions of Law of Ships in Taiwan include prohibition of sailing, with sailing allowed after improvement and payment of fines.

The improvement of an early warning system against bad weather conditions was recommended, as well as the establishment of a ship seaworthiness and wave resistance specifications. Seaworthiness means the ship's fitness and preparedness for sailing as well as its essential capability to navigate through various sea conditions while ensuring the safety of the crew and cargo. Its standard extends to all aspects of a ship, including the human element, physical structure, documentation, cargo worthiness, and so on [81]. The wave resistance specification refers to the simulated data based on the ship design data before the ship is built. As a result, both the seaworthiness and wave resistance specifications are crucial to ensure the safety and efficiency of maritime transportation. When the sailing plan may pass through sea areas with bad walrus density or exceeding the seaworthiness rating of the ship, it is necessary to avoid sailing in such sea areas or change the route as soon as possible. The automatic identification system was designed to set-up a ship collision warning mechanism [82–84]. To manage sea traffic, the vessel traffic service was used to warn ships that violated regulations and were at the risk of collisions [85,86]. Coastal patrol radar and motorized radar vehicles assisted in identifying abnormal dynamic reports of ships and provide early warning to prevent ship collisions. Furthermore, the decision-making group also advocated for relevant crew education and training materials that complied with the IMO's regulations, conducting competency assessment training for crew members and implementing international regulations and standards, such as the Maritime Labour Convention, for improving the crew's work safety awareness and mental states.

As for the mitigation measures for the consequences of ship collisions, in addition to the annual maritime accident prevention and relief drills held by the central government, all departments involved should formulate their own contingency plans or standard procedures to mitigate and reduce the consequences of the ship collision incident. For example, the coast guard association used the Search and Rescue Optimal Planning System to simulate a map with the estimations of the search area where people fell and to provide duty information for patrol ships and helicopters to increase the rescue probability for missing people. Moreover, the ocean conservation association conducted large-scale marine oil pollution monitoring through satellite images and used drones to confirm the polluted area. This would help in effectively predicting the drifting route of marine oil pollution as would immediately implementing the deployment of oil ropes and degreasing agents to prevent marine environment pollution.

This study was limited to the different backgrounds of the members in the decision-making group. The more people there are in a group, the more difficult it is to reach a consensus on the representative risk factors of ship collisions. In addition, two captains had significantly different points of view from the merchant captain, shipping companies, and port management departments, after taking their experience or academic backgrounds into consideration. Therefore, they had difficulties reaching a consensus in the beginning, but, fortunately, they were "in the same boat" eventually. The decision-making process of this study was based on the experience and expertise of experts to study the regional characteristics of maritime incidents in the Taiwan region rather than to judge on the basis of statistical data. The relevant risk factors were also analyzed through reliable literature. As a result, this study did not add relevant maritime accident statistics from IMO and EMCIP reports.

Ship collisions are only one aspect of maritime accidents. The method and model established in this study can also be applied to other analyses and topics of maritime accidents, such as ship sinking, fire, grounding, or explosion, to effectively reduce the risks of various maritime accidents and create a safer navigation environment around the sea. For future research suggestions, it may be possible to optimize continually and create a package or library that facilitates the computations.

5. Conclusions

Due to the particularity of the geographical environment and the attributes of relevant maritime survey reports in the waters of Taiwan, we adopted an integrated research method

to conduct a risk assessment and analysis of ship collision events. The research found that this method of analysis can also achieve the effect of risk assessment and management through the experience and knowledge of local experts in other sea areas with special geographical and hydrological characteristics. In conclusion, we summarized 29 risk factors through a literature review, including 15 human-made factors, 9 ship-relevant factors, and 5 environment-related factors. We extracted the representative risk factors with high relevance, high influence level, and high incidence rate by the selection of criteria specified by the decision-making group and performed calculations using RST and ROSE2. Among all, four human-made factors, one ship-relevant factor, and two environment-related factors were selected.

The human-made factors of ship collisions, including carelessness, improper operation of equipment or machinery, and unfamiliarity with local navigation regulations and ship characteristics, were the most causal and influential risk factors. In addition, the equipment and management of the ship were also factors contributing to ship collisions. For example, the steering gear of a ship is one of the most important pieces of equipment to control the ship, and the malfunction of the steering gear would affect the operational ability and increase the probability of a ship collision.

For environment-related factors, poor weather and sea conditions not only affected the visibility when the traffic density was high but also greatly influenced crew members' mental conditions and ability to make judgments.

To cope with a great number of large-scale ships and the explosive growth in shipping, the demand for crew members has relatively increased. Since human negligence is the main reason for ship collision incidents, the establishment of a retention and elimination policy might be a company's management strategy to create and maintain a good awareness of ship safety. In addition, pre-employment education and training specified for the main trafficking routes of the company, including the basic troubleshooting of machinery and equipment, navigation-related specifications, and ship characteristics, should be implemented. Moreover, we should establish a standard operating procedure for repair and maintenance on shipboard. In addition to executing annual repairs in accordance with the relevant inspection regulations of the Shipping Law, the annual repair and maintenance expenses should also be increased along with the aging of the ship. The critical equipment related to navigation safety should be replaced with new ones to reduce the incidence of ship collisions and other consequences, such as marine environmental pollution. This ensures the safety of personnel and the navigation environment.

The results show that through such a research method, we can manage and control multiple risk factors at the same time and through a clear and visualized risk analysis diagram, including reasons, prevention, and mitigations of the incidents, so that we can clearly determine the cause of a ship collision and its related preventive measures intuitively.

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Abbreviations

BTA	**Bow-tie analysis**
ETA	Event tree analysis
FTA	Fault tree analysis
FSA	Formal safety assessment
IMO	International Maritime Organization
IS	Information system
ROSE2	Rough Set Data Explorer
RST	Rough Set Theory
TSS	Traffic separation scheme

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