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Analysis and countermeasures on ship failures during navigation in the CJK Fairway based on the FTA Method

Xin Zhuang

WORLD MARITIME UNIVERSITY
Dalian, China

ANALYSIS AND COUNTERMEASURES REACHER ON SHIP FAILURES DURING NAVIGATION IN THE CJK FAIRWAY BASED ON THE FTA METHOD

By

ZHUANG XIN
The People's Republic of China

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ENVIRONMENTAL MANAGEMENT

2020

DECLARATION

I certify that all the materials in this dissertation that are not my own work have been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views, and are not necessarily endorsed by the University.

Signature: ________________

Date: 28 September, 2020

Supervised by: BU Renxiang

Professor from Dalian Maritime University

Assessor:

Co-assessor:

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ABSTRACT

Title of Dissertation: **Analysis and Countermeasures on Ship Failures during Navigation in the CJK Fairway Based on the FTA Method**

Degree: **MSc**

In recent years, ship failures during navigation have frequently occurred in the Chang Jiang Kou (CJK) Fairway of Shanghai port, and showing an increasing trend, which has brought huge challenges to the local environment and navigation safety of ships. This dissertation takes ship failures in the CJK Fairway as the research object, makes analysis (to the factors leading to the failures) and points out that the unique hydrological characteristics and the complex navigation environment of the CJK Fairway are the external causes of frequent ship failures, and poor ship management and human factors are the internal causes of frequent ship failures. Based on the ship failures data accumulated by the local maritime authorities in the past five years, the author sorts out the pattern for the ship failures. By using the Fault Tree Analysis (FTA) method, a Fault Tree with ship failures during navigation in the CJK Fairway as the top event is established, and qualitative and quantitative analysis are carried out. Based on the results of the analysis, the author puts forward to relevant stakeholders the feasible measures for reducing the ship failures in the CJK Fairway. At the same time, future challenges are also discussed.

KEY WORDS: CJK Fairway, ship failures during navigation, FTA

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LIST OF ABBREVIATIONS

DMU	Dalian Maritime University
WMU	World Maritime University
CJK	Chang Jiang Kou
FTA	Fault Tree Analysis
VTS	Vessel Traffic Service
MSA	Maritime Safety Administration
IMO	International Maritime Organization
SOLAS	International Convention for the Safety of Life at Sea
MARPOL	International Convention for the Prevention of Pollution from Ships
STCW	International Convention on Standards of Training, Certification and Watchkeeping for Seafarers
MLC	Maritime Labour Convention
ISM	International Management Code for the Safe Operation of Ships and for Pollution Prevention
RO	Recognized Organization
LNG	Liquefied Natural Gas
TSS	Traffic Separation Scheme
AIS	Automatic Identification System
SMS	Safety Management System
ETA	Event Tree Analysis
NASA	National Aeronautics and Space Administration
ME	Main Engine
DOC	Document of Compliance
PSCO	Port State Control Officer
PSC	Port State Control
FSC	Flag State Control
MOU	Memorandum

CHAPTER 1 INTRODUCTION

1.1 Background

Shipping, as an important carrier of international transportation, has made extraordinary contributions to the development of world interconnection, globalization and global economy by transporting more than 80 per cent of global trade to peoples and communities all over the world (IMO, 2020). However, according to IMO (2002), "While shipping is one of the most international industry of all the world, it is also perhaps one of the most dangerous." In the process of ship's operation, it is necessary not only to resist external risks such as severe weather, complicated navigation environment, piracy, etc., but also to prevent internal risks such as ship equipment failures, poor maintenance, structure of the ship, special features of the goods, and human errors, etc. To this end, maritime stakeholders such as Member States, IMO, classification societies have performed their duties and worked together to formulate a large number of maritime regulations in the field of enhancing the safety of ships and public safety, such as SOLAS, MARPOL, STCW, MLC, ISM Code and Rules of RO (Recognized Organization).

However, these regulations have not been able to prevent ship failures or accidents completely. What we can do is to find out the factors that affect the safe operation of ships by analyzing the risks as comprehensively as possible, and devote our limited energy to those special factors so as to minimize safety threat to the ship.

Ship failures during navigation refer to such a state of the ship: when the ship is navigating at sea as scheduled, a sudden failure of the machinery or equipment on board the ship may occur which cannot be repaired immediately, making the ship unable to sail according to the officer's wishes, and the ship's maneuvering is restricted or the ship is completely out of control. Cases have shown that in the densely nearshore channel, limited operations or loss of control due to ship failures will give rise to an urgent situation for surrounding ships, and may lead to block of the channel, collisions, oil spills, sinking of ships, or even serious casualties.

Fault Tree Analysis (FTA) is one of the important methods often used in safety system engineering. It is mainly used to identify and evaluate system hazards. It can not only analyze the direct causes of accidents, but also reveal the potential causes of accidents in depth (Lin & Zhang, 2007). FTA is a widely used technique to estimate the safety and reliability of safety-critical systems (Qiao, Liu, Ma & Liu, 2020), such as ship grounding accident cause analysis (Kum & Sahin, 2015), explosions in oil tankers (Wang, Zhang & Chen, 2013) and LNG carrier accident analysis (Zhou, Wu, Zhang & Zhang, 2017). Zhou, Wang and Ding (2002) established a fault tree about ship engine room fires, gave the structural importance ranking of each basic event through analysis, and proposed preventive measures. Yao, Ren and Li (2010) took ship collision accidents as an example, and established a fault tree based on the various factors affecting collision accidents. After making analysis, they obtained the importance coefficient of each factor and put forward measures for controlling ship collision accidents.

Fault tree analyses were used in the above-mentioned literature, and the influencing factors of each research object can be identified more clearly, which has a positive effect on improving management methods.

1.2 Target and objectives of the research

The target of the research is ship failures during navigation in Shanghai Chang Jiang Kou (CJK) Fairway, which include North Deep-water Fairway, Extend Fairway of the deep-water route and South Fairway. These areas are under the coverage of Wusong Vessel Traffic Service (VTS) center, and are under administration of Wusong Maritime Safety Administration (MSA) which is one of the branches of Shanghai Maritime Safety Administration (Shanghai MSA).

Statistics show that in recent years, ships in Shanghai's CJK Fairway have experienced frequent failures and the situation is becoming worse. Ship groundings, collisions and even oil spills are often related to ship failures, posing a major threat to the good order and safety of navigation, ship safety, crew life and the local marine environment.

This paper analyzes a large number of ship failure data accumulated from 2015 to 2019 on the Shanghai CJK Fairway, classifies the causes for ship failures, identifies common factors that affect ship failures, and builds a fault tree based on the analyses. Through qualitative analysis and quantitative analysis, the importance of each basic event affecting ship's failures is calculated. Based on the calculation results, it provides reasonable suggestions on reducing ship failure rate to stakeholders such as ships, ship management companies and competent maritime authorities.

1.3 Methodology

In order to achieve the objectives of the research, this paper uses a variety of research methods, such as data summary, case analysis, questionnaires and the FTA method.

Firstly, a statistical analysis of 895 ship failures that occurred in the Shanghai CJK Fairway from 2015 to 2019 carried out, and the elements analyzed include the time and location of the failures, type of the ships, the cause of the failures. In this way, the common pattern leading to the failures is summarized.

Secondly, typical cases are selected for making deep analysis to the causes of ship failures.

Thirdly, as the key research method of this paper, based on the results of data analysis, different ship system failures that caused ship failures are regarded as intermediate events, and the specific causes of system failures are regarded as the basic events. The paper establishes a formal fault tree based on the logical relationship between basic events and intermediate events, conducts a qualitative analysis based on the FAT method, and then carries out a quantitative analysis based on the average value assigned by ship management experts to the probability of each basic event.

Based on the conclusions drawn from the above research methods, suggestions for reducing ship failures will be put forward.

1.4 Structure of the dissertation

This dissertation consists of 6 chapters. Chapter 1 introduces the background, target, objectives and methodologies the research will use. Chapter 2 introduces the hydrologic and navigation characteristics of the CJK Fairway, and introduces the total numbers, types and characteristics of ship failures in the CJK Fairway in the past five years. The hazards of ship failures are also discussed, and two typical cases are analyzed. Chapter 3 provides patterns for ship failures in CJK Fairway. Chapter 4 provides the FAT theory, and ship failures in CJK Fairway are analyzed in detail using the FAT method. Chapter 5 provides relevant recommendations based on the FAT analysis, and challenges are also discussed. Chapter 6 is the conclusion of the dissertation.

CHAPTER 2 THE CHARACTERISTICS OF THE CJK FAIRWAY AND HAZARDS OF SHIP FAILURES

2.1 Hydrological characteristics of the CJK Fairway areas

The CJK Fairway areas are located at the entrance of the Yangtze River into the East China Sea. Due to the large amount of sand in the Yangtze River water body (Bao, Peng, Bao & Lou, 2020), under the years of alluvial accumulation, the sedimentation of the Yangtze River Estuary waters is obvious (See figure 1). The natural water depth is only 5-7 meters, and some shallow points are even less than 3 meters. With the development of larger-sized vessels, the natural water depth cannot meet the draft needs of large ships. Therefore, the Chinese government has invested a huge amount of money since the 1990s, and gradually dredged a Deep-water route with a width of 350-400 meters and a water depth of 12.5 meters, and South Fairway with a water depth of 7 meters.

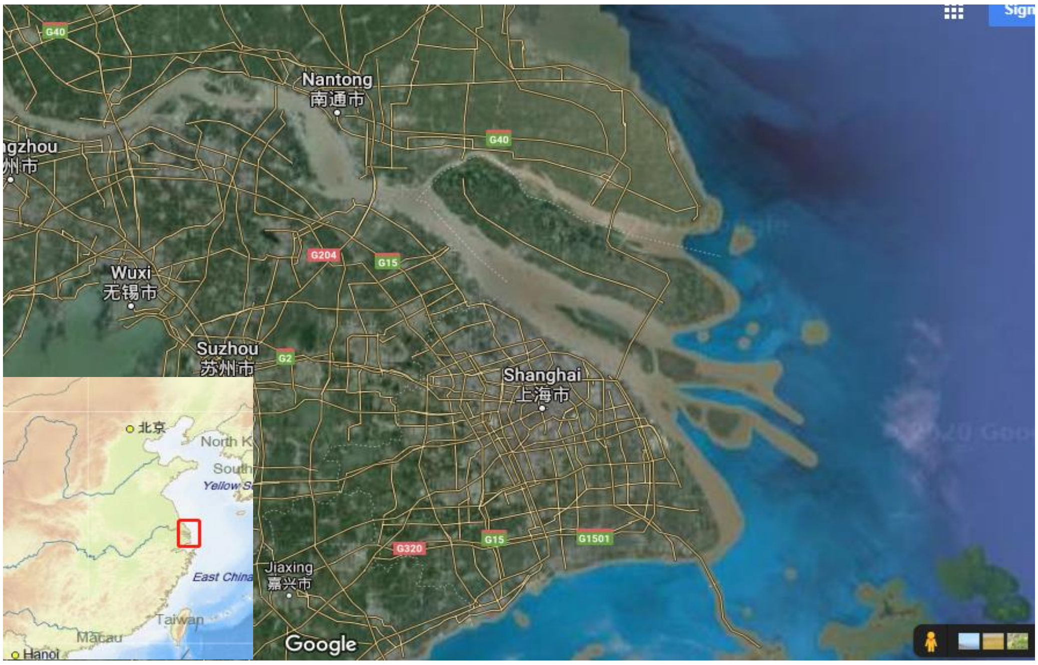


Figure 1 - Satellite picture of the Yangtze River Estuary
Source: Google map

The estuary area is a complex environmental system that is affected by the combined action of river basin runoff and ocean tides. The tidal waves in the estuary have completely different characteristics from the regular tide waves in the ocean. The tidal spectrum of the estuary develops to a more complex shallow-water tidal spectrum, and the tidal wave energy is redistributed, making the tides show significant nonlinear deformation and asymmetry. The estuary of the Yangtze River is a tidal estuary of moderate intensity with irregular half-diurnal tides (Cao &Ji, 2018). The maximum and average tidal range can reach 4.62m and 2.67m respectively (Lu, Wu & Tong, 2019).

In winter, the Yangtze River estuary is often hit by cold waves, which bring strong winds and waves. In summer and autumn, typhoons in the Western Pacific often affect the region. Strong winds with wind force greater than 6 prevail for an average of 63 days per year, and strong winds with wind force greater than 7 last for an average of 42 days per year. In addition, in winter and spring, foggy weather often occurs, with an average annual foggy day of 28.8 days (Dong, 2015).

Unlike in other coastal ports in China, the unique hydrologic characteristics of the estuary make it more difficult for ships to navigate in the CJK Fairway, because the main engine rotation speed and rudder angle of the ship should keep changing to maintain the course of the ship. Fog and high winds also pose challenges to the officers on board the ships.

2.2 Navigation characteristics of the CJK Fairway

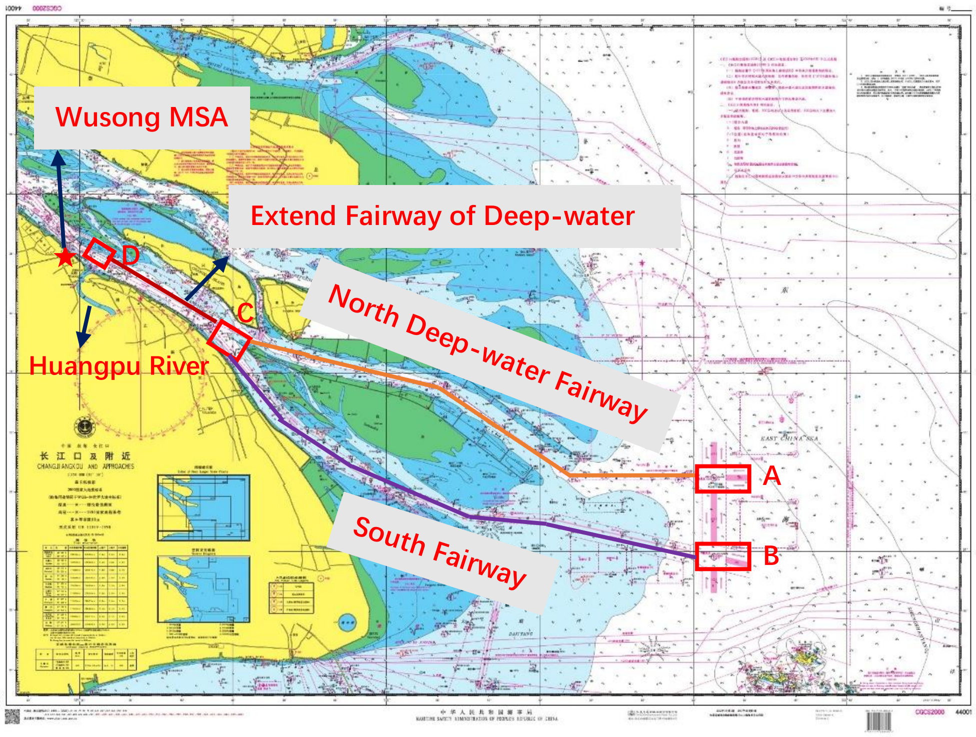


Figure 2 - Schematic diagram of the CJK Fairway
Note: A: CJK A precautionary area B: CJK B precautionary area
C: Yuan Yuan Sha precautionary area D: Wu Song Kou precautionary area
Source: China MSA

Figure 2 above is a schematic diagram of the CJK Fairway. The CJK Fairway includes the CJK Deep-water Fairway (54 nautical miles) and South Fairway (45 nautical miles). The CJK Deep Water Fairway is divided into two parts: North Deep-water fairway (43 nautical miles) and Extend Fairway of Deep-water (11 nautical miles).

The Traffic Separation Scheme (TSS) is implemented in CJK Fairway, and Wusong VTS center which is one of a department of Wusong MSA， provides traffic organization service, information service and navigation aids service for the water areas.

The provinces near the mouth of the Yangtze River are the most economically developed regions in China, with huge international trade volume, and the mouth of the Yangtze River is the only way for ships to enter the hinterland of China, as a result, the flow of ships is very dense in the CJK Fairway. It can be seen from Table 1 that in the past three years, there were 170-190,000 navigable vessels in the CJK Fairway annually, and the total number of navigable vessels is on the rise. Figure 3 is a real-time navigation dynamic map generated based on the ship's Automatic Identification System (AIS) signal, and each triangle represents a ship. It can be intuitively felt from the picture that traffic in the CJK Fairway is very dense.

Table 1 - The total number of navigable vessels in the CJK Fairway in the past three years

	North Fairway	South Fairway	Total
2017	69,799	105,394	175,193
2018	63,043	110,901	173,944
2019	64,644	124,857	189,501

Source: Wusong VTS

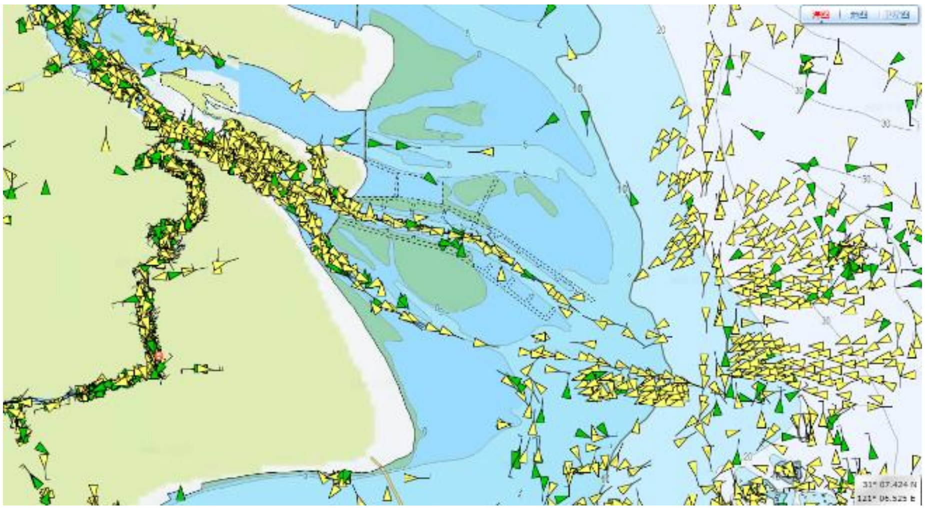


Figure 3 - Real-time navigation dynamic map of the CJK Fairway
Source: http://www.shipxy.com/

Since the deep-water route is an artificial dredging channel and the width of the channel is limited, deep draft ships must strictly follow the channel direction when navigating in the deep-water channel. Leaving the channel will cause the ship to ground.

In addition, there are many meeting points for ships in the CJK Fairway. For example, in the Yuan Yuan Sha precaution zone in Figure 2, large ships in the North Fairway will meet with ships in the South Fairway; in the Wu Song Kou precaution zone, ships sailing on the Yangtze River will meet Ships going in and out of the Huangpu River or ships in and out of the Wusongkou anchorage. Since small vessels like to sail by tide to save fuel, the density of ships in a day is not evenly distributed. During the transitional period from low tide to high tide, the Wu Song Kou precaution zone will be very dense with ships, making it the most complicated navigation environment in the CJK fairway.

The unique hydrological and navigable characteristics make the waters of the CJK Fairway one of the busiest channels in the world. When a ship sails here, the seafarers need to keep focus at all times and keep a safe distance from the surrounding ships, and the engineers should ensure that the power equipment in the engine room are always in a reliable operation state and maintain the ship's good maneuvering performance.

2.3 The number of ship failures during navigation in the CJK Fairway in recent years

According to Regulation 15 of the "Measures for the Administration of Navigation Safety of the CJK Deep-water fairway" issued by Shanghai MSA, "If an accident or dangerous situation occurs or is discovered on a ship, there is or is suspected of having hull, power equipment, control equipment and other abnormal conditions that affect navigation safety, the ship should notify surrounding ships in time and report to Wusong VTS Center at the same time." (Shanghai MSA, 2018).

The author made a statistic on the ship failure data received or discovered by Wusong VTS center in the CJK Fairway during the past five years from 2015 to 2019. As shown in Figure 4, a total of 895 ship failures occurred during the five years from 2015 to 2019. There were 99 ships failures during navigation in the CJK Fairway in 2015, but in the following four years, the number of ship failures increased year by year. In 2017, the number of ship failures increased significantly with an increase of 87% compared with the figure in 2016. In 2019, a historical record was set for 259 ship failures in the fairway, and an average of 5 ship failures occurred every week, which was 2.6 times that of 2015.

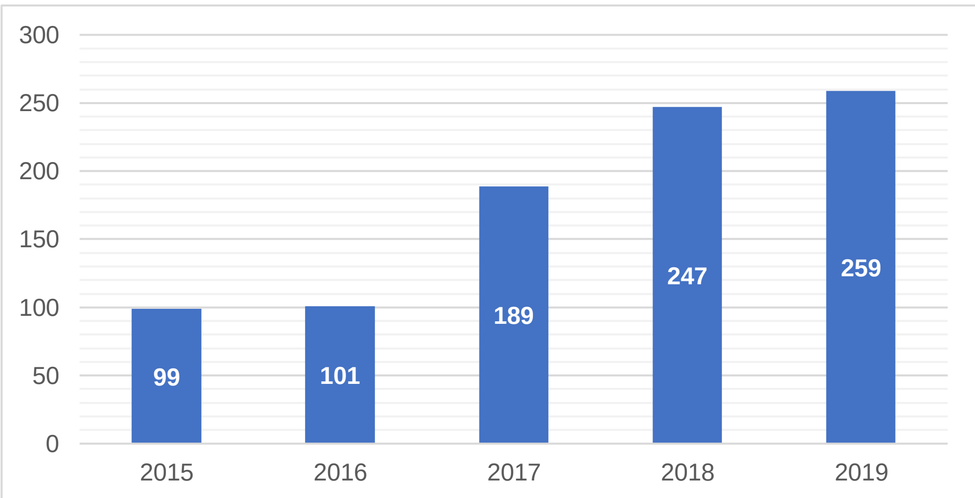


Figure 4 - Number of ship failures in the CJK Fairway from 2015 – 2019
Source: Author

According to statistics from Wusong MSA, nearly 50% of the ship accidents in the jurisdiction are related to the loss of control caused by the ship's failure. It can be said that the situation is very serious whether from the perspective of the accidents that may be caused by ship failures or from the increasing trend of the number of ship failures. Therefore, conducting research on ship failures, discovering the patterns and root causes, and making suggestions to reduce ship failures is of great significance to maintaining the safety and stability of the CJK Fairway.

2.4 Hazards of ship failure in the CJK Fairway

In view of the special hydrological and navigable characteristics of the CJK Fairway water areas, the failure of ships in CJK Fairway during navigation is very harmful. Ship failures can make the ship slow down or face restriction in operation, and even make the ship lose control and lead to secondary accidents. In the following parts, the paper analyzes the hazards of ship failures from the perspective of the impact on ships, crews, management companies, the environment and the navigation environment.

2.4.1 Hazards to ships

The failure of the ship firstly will make the ship unable to sail normally, the operation was restricted or completely out of control, and the tugs will be required to tow the ship to the nearest anchorage for repair. If the fault is caused by damage of machines, spare parts often need to be imported from abroad if the ship has no spare parts on board, and the ship has to wait in the anchorage for many days, which will cause the delay of voyage. If the ship collides with another ship or runs ground, the structure of the ship may be damaged and needs to be repaired at the shipyard, which will also cause delays in the shipping schedule. In the most severe case, a ship collision will cause the ship to sink.

In addition, the Shanghai MSA will send Port State Control Officers (PSCOs) to go on board the ship for inspection if the ship failure at the entrance channel of the CJK Fairway. Compared with the inspection of ships in normal operation, PSCOs will inspect the failure ships in more details. If serious deficiencies are found, the ships will be detained immediately until the relevant deficiencies are rectified. This can be seen as a punitive measure taken by local maritime authorities for promoting the level of ship management.

2.4.2 Hazards to crew

The crew will feel nervous and stressful when a ship breaks down in the CJK Fairway, and carries this emotion in repairing the fault. Under high stress conditions, the judgment and execution capacity of the crew will be greatly reduced, and human error is more likely to occur which will lead to secondary accidents.

In addition, collisions caused by ship failures will directly threaten the safety of crew members.

2.4.3 Hazards to ship management companies

For ship management companies, voyage delays and ship repairs caused by ship failures will increase ship operating costs and reduce operating revenue. If the vessel frequent failure caused frequent delays, it will reduce the company's reputation, and resulting in reduced cargo supply. If the ship is detained during the Port State Control (PSC) inspection after the failure, it will also lead to the degradation of the company's performance, which may result in the shortening of the PSC inspection window for the ships managed by the entire company.

In addition, if collisions and oil spills occur after a ship failure, the company will also face a huge claim from parties concerned.

2.4.4 Hazards to the environment

The collision caused by the ship's failure may cause oil spills and seriously damage the ecological environment of the Yangtze River Estuary. The Yangtze River is the main source of drinking water in Shanghai, and if there is a large-scale oil spill, the safety of drinking water for Shanghai residents will be seriously threatened.

2.4.5 Hazards to navigation environment

The CJK Fairway is an artificial dredging channel. Ships with a draft of more than 7 meters can only navigate safely in the deep-water route. If large vessels break down in the deep-water channel and cannot be repaired in a short time, the "golden waterway" of the Yangtze River will be blocked directly, making it impossible for other large vessels to enter or leave normally.

2.5 Analysis of typical ship failure cases

Case 1:

At 15:20 on July 28, 2017, when an oil tanker called “YU SHUN 217” navigated in the entrance channel of Extend Fairway of Deep-water route, the connection ring of the hydraulic oil pump of the steering gear suddenly broke. As a result, the steering gear lost hydraulic power, and the rudder angle was stuck at amidships and cannot be changed.

The failure of the steering gear made “YU SHUN 217” unable to change her course in the busy CJK Fairway, so the captain immediately slowed down the main engine to reduce the speed of the ship. But as the speed decreased, the ship's course became unstable under the influence of the water flow and begins to turn sharply to the port side. The helpless captain could only watch “YU SHUN 217” to collide with the bulk carrier “XIN HAIFU” which was navigating in the same direction on the port side at buoy D51 ten minutes after the steering gear failure happened.

The gross tonnage of “XIN HAIFU” is 8236, while the gross tonnage of “YU SHUN 217” is 499. Due to the large tonnage difference, “XIN HAIFU” was not significantly damaged after the collision, but there were multiple cracks in the port side of “YU SHUN 217”, and the bulkhead of its No. 2 cargo hold was cracked.

After the collision, water flooded into “YU SHUN 217” and the ship listed to portside. In order to maintain the stability of the ship and prevent the ship from overturning, the captain of “YU SHUN 217” directly pumped out nearly 88 tons of fuel oil loaded in the port No. 2 and No. 3 holds into the Yangtze River, which resulted in a severe pollution to nearby waters (see Figure 5).

Figure 5 – Failure of “YU SHUN 217” caused a severe oil pollution
Source: Author

Case 2:

At 20:35 on April 28, 2018, when a ship called “HUA JIANG 10” navigated near buoy D41 of North fairway entrance channel, the main engine suddenly stopped and the engineer could not find the cause, which rendered the ship out of control. The diesel engine of generator was also stopped 15 minims later, and the ship was blacked out. Although the master wanted to use the remaining speed to guide the ship to safe waters, but the speed of the ship dropped quickly after power off, and the ship immediately lost control completely.

In order to control the ship from colliding with nearby ships, the master dropped an anchor regardless of the fact that the ship was in the no-anchor zone with communication cables buried under the water. However, due to the excessive inertia of the ship, the connection between the anchor chain and the hull broke, and the ship did not stop as the master planned. Subsequently, the ship was pushed to a shallow point by the current and grounded, which led to the list of the ship.

Fortunately, the anchor did not cause any damage to the underwater cables. The ship was pulled out with the assistance of the tug at nest high tide, and there was no oil spill.

When the maritime investigation officer boarded the ship to investigate the cause of the failure, it was discovered that the ship's loss of control was caused by human error. The chief engineer of the ship had just shifted on board at the previous port and was working on that ship for the first time. When the chief engineer toured the engine room before the incident, he found that the carbon dioxide release control box for the oil purifier room was not properly closed, so he opened the box and closed it again. However, for fire safety considerations, there is an interlock device in the control box (see Figure 6). When the release box opened, the power of fuel supply pump and the fan of the engine room will automatically be cut off, but the chief engineer had no idea about it. The main engine stopped in no time due to the lack of the fuel.

After the main engine stopped, the chief engineer found that the fuel pump switch in the engine control room was disconnected, but the switch couldn't be switched on. Because as the design of the fuel supply system of the ship, the system should be reset at the fuel oil supply unit firstly after being switched off, but the engineers of the ship did not know that, so the fuel pump could not be started again. Fifteen minutes later, the diesel engine of generator ran out the fuel in the pipeline and stopped working led to black out. The fault was not removed until the ship ultimately grounded.

Figure 6 - Interlock device in CO_2 release control box
Source: Author

CHAPTER 3 REGULARITIES OF SHIP FAILURES IN THE CJK FAIRWAY

3.1 Types and characteristics of ship failures in the CJK Fairway during 2018 and 2019

The author analyzed all 506 ship failure records collected by Wusong VTS in 2018 and 2019 one by one, and classified them according to the causes of ship failures. All the cases are divided into main engine failure, steering gear failure, cooling water system failure, black out and generator engine failure, etc. The main engine failures are subdivided into the main engine component failure, main engine fuel system failure, main engine cooling system failure, main engine electronic system failure, main engine control system failure and main engine lubricating oil system failure. The analysis of the data lays the foundation for the research in the following parts.

3.1.1 Analysis to main engine failures

Judging from the causes of failures reported to Wusong VTS by ships, main engine failures have been the main cause of ship failures over the years. In 2018, a total of 186 ship main engine failures occurred in the CJK Fairway, accounting for 80% of all failures that year; in 2019, 194 ship main engine failures occurred in the CJK Fairway accounting for 75% of failures for the year.

Due to the similar causes of main engine failures in each year, only the main engine failure events in 2019 are analyzed in detail here.

Table 2 - Analysis of the main engine failure of the CJK Fairway in 2019

Type of failures	Number of failures	Proportion	Causes
Main engine component failure	78	41.2%	Failure of governor, supercharger, exhaust valve, cylinder head start valve, piston ring, cylinder liner, bearing and other wear and pressure parts
Main engine fuel system failure	62	31.9%	High-pressure oil pipe rupture, high-pressure oil pump failure, fuel injection nozzle clogged, oil pump suction filter blocked
Main engine cooling system failure	29	14.9%	Sea water suction filter blocked、cooling pipe rupture
Main engine electronic system failure	11	5.7%	Short out of circuit board
Main engine control system failure	8	4.1%	Air control system failure、Control element failure
Main engine lubricating oil system failure	6	3.1%	Low lubricating oil pressure due to filter blocks

Source: Autor

Table 2 above shows the common categories of main engine failures, and the following is a detailed analysis to the causes of main engine failures:

1) Main engine component failures

It is the largest number of failures by this type all of failure throughout the year which accounts for 41.2% of total failures. According to the data statistics, the failure probability of the pressure-bearing and wear-prone parts in the main body parts is higher. For example, stuck of the cylinder exhaust valve, worn of the turbocharger bearing and the breakdown of turbocharger screws, turbines and other small components take up a large number of all faults.

On the one hand, the working environment of such parts is poor and it is indeed prone to wear and tear. At the same time, the frequent occurrence of such failures also reflects that the daily maintenance and inspection of the main engine of the ship is not in place, and the company's maintenance of the fleet is insufficient, or Safety Management System (SMS) operation relate to main engine maintenance is not in a good order. For example, as for cylinder liner wearing, after on-site inspection by the MSA officer, it was found that most of the engineers did not pre-pressure the lubricating oil according to the requirements of the SMS documents before starting, which leading to the occurrence of cylinder wearing.

2) Main engine fuel system failures

The fuel system failure accounts for a high proportion and has distinct characteristics. From the data analysis in 2019, the main engine high-pressure fuel pipe rupture, high-pressure fuel pump failure, and high-pressure fuel nozzle blockage have become the three most common faults in the fuel system. From the high-pressure fuel pump to the fuel pipe and the fuel nozzle, it is the last step before the ship's fuel enters the cylinder, and it is also the part with the greatest pressure in the entire fuel system. The root cause of the failure is that the components are damaged by long-term high pressure.

This type of failure is one of the common types of failures of ships and has attracted the attention of the industry. According to SOLAS (2014) Chapter II-2 Regulation 4.2, “External high-pressure fuel delivery lines between the high-pressure fuel pumps and fuel injectors shall be protected with a jacketed piping system capable of containing fuel from a high-pressure line failure.”, and “The jacketed piping system shall include a means for collection of leakages and arrangements and shall be provided with an alarm in case of a fuel line failure.” Ships should pay great attention to this, and maritime departments should also carry out related inspection.

In addition, in the case of fuel system failures, the blockage of filters is also very common, which indicates that the maintenance of the fuel filter by engineers is not good enough.

3) Main engine cooling system failures

In 2019, a total of 29 ships met with main engine cooling system failures when navigating in the CJK Fairway, which led to slow down of the engine. The main failure types can be divided into two categories, one is the clogging of the seawater inlet filter, and the other is the rupture of the cooling water pipe. According to the investigation, the filter or water pipe were mostly blocked by small fish groups, leading to the failure of cooling water supply. Such faults have their own seasonal pattern and often occur more frequently in fish season every year. The main causes of water pipe rupture were aging and corrosion of water pipe and lack of daily inspection and maintenance of cooling water pipe.

4) Failures in main engine electronic system, control system and lubricating system

The number of failures involving the main engine electronic system, control system and lubricating oil systems throughout the year was not high, accounting for about 14%. The overall performance is that the control unit circuit board is short-circuited, the control system components are aging, and the oil pump is faulty resulting in low pressure. Sometimes, a certain ship failure will cause the failure of other systems, such as the failure of the ship's lubricating oil system will often causes the main engine cylinders abnormal wear and damage the cylinder liner.

It should be noted that the causes of such failures on some ships were related to the rude operations of ships. For example, in order to overcome the rapid fluctuation of tide in the deep-water channel or overtake the forward ship, the ship suddenly increased the load, leading to the failure of the main engine due to too high load. Before ships entering the CJK Fairway, or during deep-water navigation, they need to make full estimation and preparation for the characteristics of the waters.

3.1.2 Analysis of all failure types

The author classified the causes of all ship failures in 2018 and 2019. The failure of the main engine was the main cause, and there were other types of failures, as shown in Figures 7 and 8:

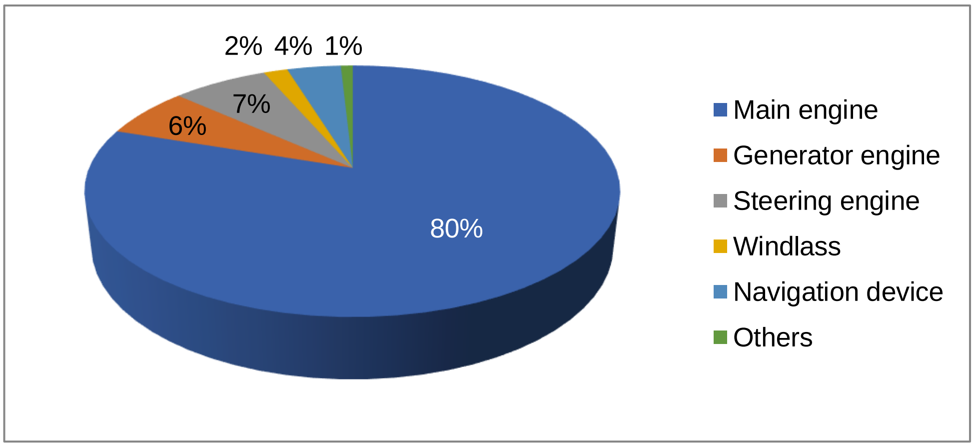


Figure 7 – Failure types in 2018
Source: Author

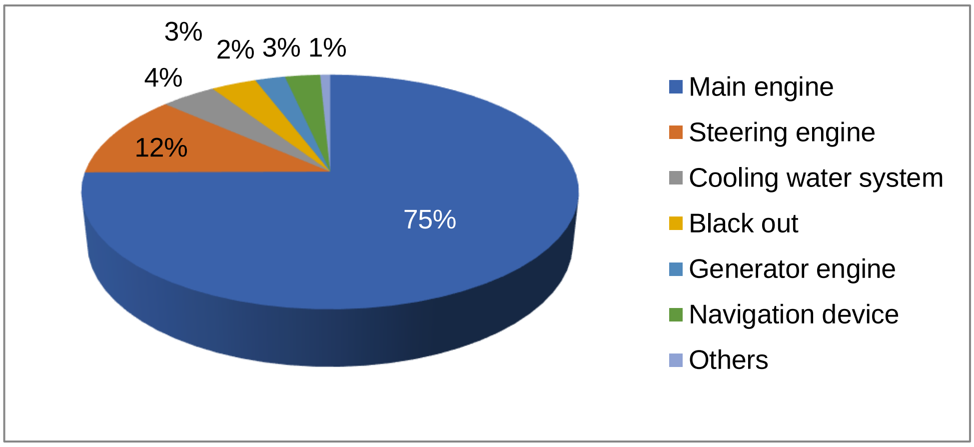


Figure 8 – Failure types in 2019
Source: Author

According to statistics, a total of 247 ship failures occurred in the CJK Fairway in 2018, of which 186 main engine failures accounted for 80% of the total annual failures, followed by steering gear failures (16 times), accounting for 7% of the total, and the third type of top failure is generator engine failures (15 times), accounting for 6%. From the data point of view, main engine failures have the largest volume, which is the most prominent problem of ship failures in CJK Fairway.

There were a total of 259 ship failures in 2019, including 194 main engine failures, accounting for 75% of the total number of annual failures, followed by 30 steering gear failures, accounting for 11.6%, and 11 cooling water system failures, accounting for 4.2%, in the third category. The main engine failure and steering gear engine failure were still the main causes of ship failures.

However, it is worth noting that although the number of steering gear engine faults were far less than that of the main engine, its influence to the ship was more obvious. Most of CJK Fairway is narrow waterway, which requires very high stability of ship's heading. The loss of rudder effect of a ship will lead to grounding, collision and other traffic accidents in a short time. Compared with ship losing power, the danger of steering gear failure is more urgent, which deserves more attention.

It would also be dangerous to lose power for the whole ship (black out). The ship will lost power and out of control if the ship's emergency generator couldn't start up and supply power in 45s by the requirement of SOLAS Chapter II-2 Regulation 43- "Emergency source of electrical power in cargo ships", and secondary accidents like collision may happen.

In addition, failures of ship's navigation aids were mainly manifested as failures of ship's AIS, radar and compass, and more than half of the failures were caused by AIS.

3.2 Ship types

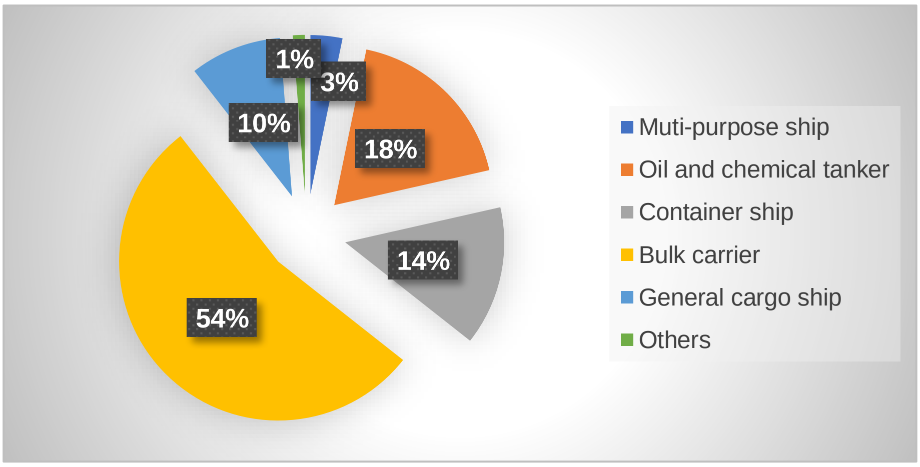


Figure 9 – Ship types of failure ships in 2018
Source: Author

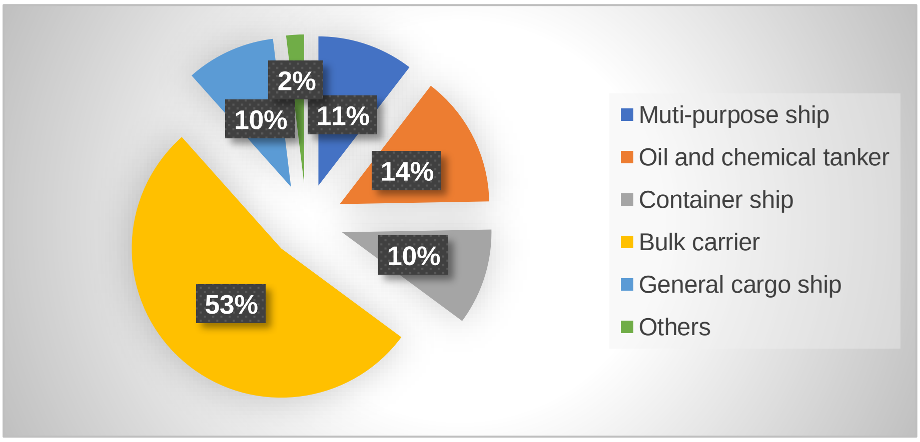


Figure 10 – Ship types of failure ships in 2019
Source: Author

From Figure 9 and Figure 10 the types of ship failures in 2018 and 2019, it can be found that the proportion of each type of failed ships has not changed much. The main types of ships that have failed are bulk carriers, oil tankers, container ships and multi-purpose ships.

The number of bulk carrier failures exceeded 50% in these two years. It is understood that bulk carriers are the ships with higher profits in the shipping market at present, and the total number of ships entering and leaving the channel is relatively high. Meanwhile, the failure rate of these ships is also relatively high among all types of ships.

3.3 Regions where failures happened

According to the statistics of the water areas where the failures occur, the ship failure distribution shows a trend of the outside water areas happened more than internal water areas, and the North fairway and South fairway are the main regions where the ship failure occurs (see Figure 11).

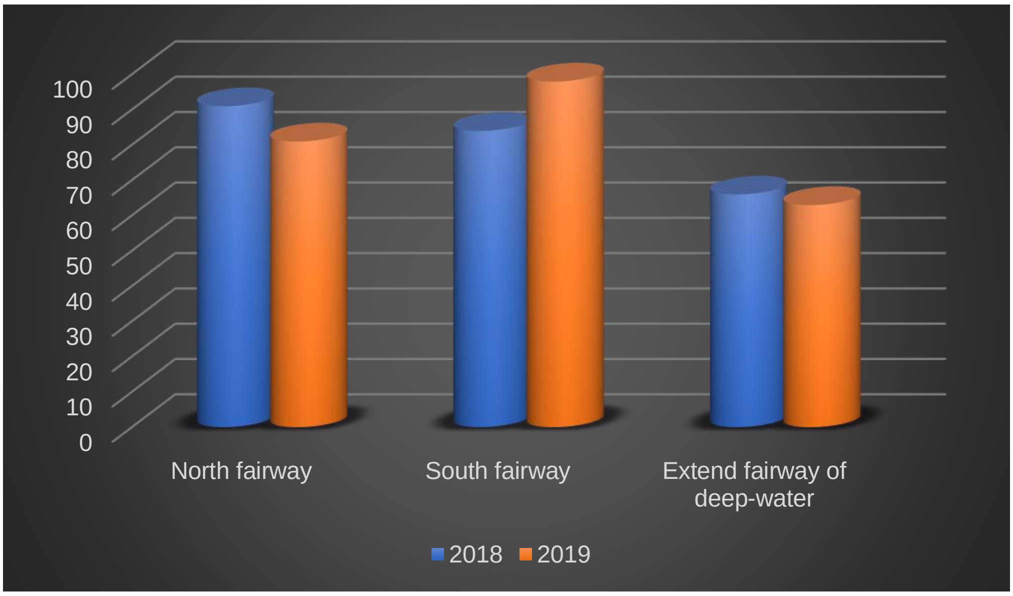


Figure 11 – Failures that took place by regions in 2018 and 2019
Source: Author

On the one hand, the North fairway and South fairway are relatively long and can accommodate a large number of ships. On the other hand, affected by the hydrologic characteristics of the channel, the current in the channel is faster, so the ships need to change the rudder angle or speed of the main engine frequently and the output power fluctuates greatly, which will easily lead to the increase of the failure rate of the ship's main engine, steering engine, generator and other equipment.

3.4 Month when failures happened

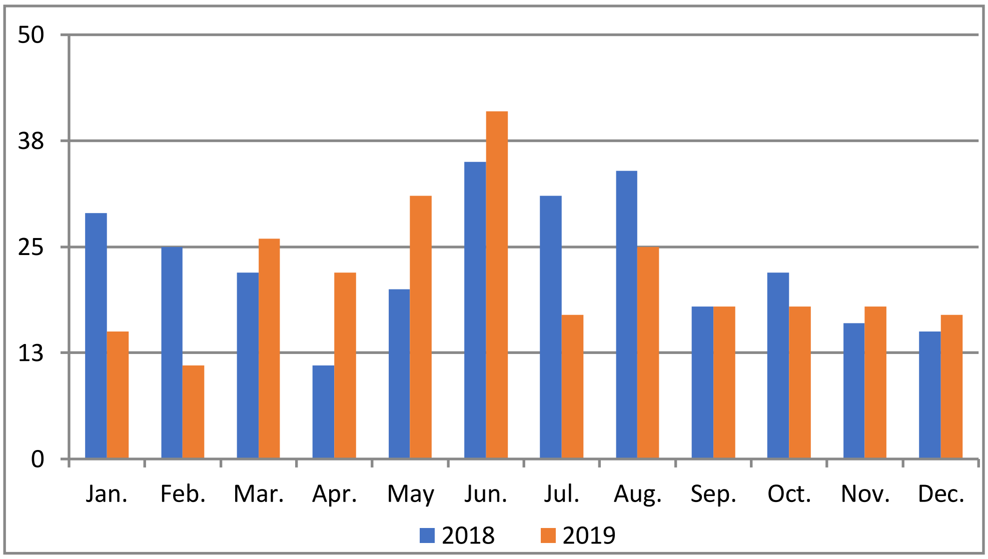


Figure 12 – Month when failures happened during 2018 and 2019
Source: Author

According to the statistics shown in Figure 12, ship failures have obvious seasonal characteristics, mainly in winter and summer. Relatively speaking, high temperatures in summer are more likely to cause various types of ship failures. On the one hand, marine electromechanical equipment work in high temperature in summer, which requires higher cooling capacity and heavier equipment load. On the other hand, the high temperature of engine room in hot season makes the working environment of engineers more severe and easy to fatigue. Therefore, the maintenance and repair of equipment may not be in place, which may easily cause equipment failure.

In addition, due to the continuous efforts of the Chinese government in environmental protection, the water quality of the Yangtze River and the ecological environment of the Yangtze Estuary have been significantly improved. In summer, wild fish in the

Yangtze River estuary increase significantly, increasing the risk of blocking the filters due to the large number of small fish that are inhaled by the seawater cooling system when the ship passed the fish school. Once the filter is blocked, the cooling capacity will be insufficient, leading to the failure of the main engine or the auxiliary engine. Such cases have increased obviously in recent years.

3.5 Human factor analysis for ship failures

Although the most direct cause of ship failures is malfunction of the main engine, steering gear and other equipment, if we analyze the causes of these equipment failures in depth, we can find that human factors play an important role in the process of equipment failures.

According to Andrea (2019), the human error is an inappropriate or unacceptable human decision or action that degrades efficiency, safety or system performance. By Catherine (2006), the human element is the most unpredictable factor, given that everyone has different behavior and understanding with the safety management not only in emergency situations but also during daily routine.

Graziano (2016) said that most accidents involve the interaction between humans, organizations and systems. Report from Allianz (2017) even stated that it is estimated that 75% to 96% of marine accidents can be attributed to human error.

Human errors can be caused by failure to maintain the equipment as required by SMS, mis-operation, fatigue, stress, communication barrier, etc. Due to the development of new technology on ship, the reliability of equipment is getting higher and higher, and the functions are becoming more and more comprehensive, but this has led to the excessive dependence of the crew on the equipment. As a result, the crews are at a loss in the event of equipment failure, and the emergency response capability is insufficient.

On the other hand, while the ships become bigger and bigger, the manning become less and less, and with more and more maritime conventions coming into force, crews on board ships undertake much more jobs than before. The rest time of seafarers are squeezed, therefore, they feel more stressful and easier to fatigue. Sanpson (2017) states that the feeling of 'severe' fatigue of seafarers has been increased from 24% in 2011 to 36% in 2016.

According to the study by Professor Baumler from WMU, people's performance will vary with different workload as shown in Figure 13. When the workload is too low, people's attention is difficult to concentrate, performance is at a low level, and the system is in an unsafe state. As the workload increases, people's performance will gradually improve until it reaches a peak, the probability of human error will gradually decrease, and the system is in a safe state. But when the workload is too heavy, people's performance will decrease rapidly after the peak, human errors will increase significantly, and the system will be in an unsafe state or out of control.

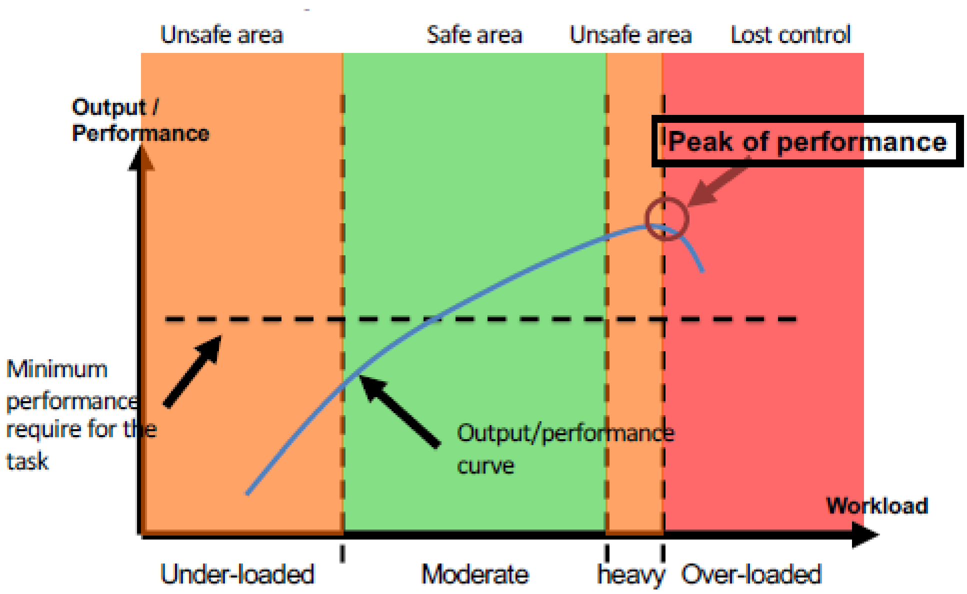


Figure 13 – Relationship between work performance and workload
Source: Professor Baumler from WMU

This is because the cognitive resources of people are limited, and demanding and complex tasks require large resources (Baumler, 2019). When people in an over-load condition, they don't have enough capacity to deal with the complex situation.

When a ship is navigating in the CJK Fairway, due to the complicated hydrological and navigable environment, the seafarers must always pay attention to ensure the safe navigation of the ship. At this time, the workload of the seafarers is already at a relatively high level or even overload. If ship failure happens at this time, it is difficult for the seafarers to have extra cognitive resources to deal with emergencies, and the crew will in an overloaded working state. According to the above analysis, the performance of the crew will rapidly decrease and human errors will increase.

Among the ship failure events in CJK Fairway, a large portion of them were related to human factors. Such as in the Case 1 mentioned in 2.5, the break of the connection ring of hydraulic oil pump was because the engineer didn't maintain the steering system as schedule. In Case 2, the direct cause of the failure is mis-operation by the chief engineer.

CHAPTER 4 ANALYSIS BASED ON THE FTA METHOD

4.1 The Fault Tree Analysis (FTA) theory

4.1.1 Overview of FTA theory

Since the early 1960s, after the application of FTA and Event Tree Analysis (ETA) in National Aeronautics and Space Administration (NASA) and the Department of Defense of America, FTA technology has experienced a development process from simple to complex, from static to dynamic, from traditional to fuzzy. In 1974, a scientific research team led by Rasmussen of the Massachusetts Institute of Technology in the United States, using FTA and ETA analysis methods, published the famous WASH-1400 risk assessment report on pressurized water reactor accidents, which caused great shock in the industry. Based on this, the FTA theory was born (Han, 2020). In 1977, Lapp and Powers proposed a non-coherent correlated fault tree model using computational automatic construction, which opened up a new method of computer automatic construction and once again pushed FTA research to a new high level (Shi & Wang, 1993). At present, as a means of evaluating system reliability and safety, FTA has been widely used in aerospace, nuclear energy, electric power, chemical industry, machinery, transportation, civil engineering and other fields.

The FTA method is a method of analyzing and diagnosing using logic block diagrams, which is widely used in equipment failure safety diagnosis and analysis. With the progress of industry, FTA has been improved and strengthened, and formed a complete program and theory, which has been developed and used a lot (Cao & Cheng, 1986).

Before understanding the fault tree theory, we must first understand the nature of the fault tree.

Essentially, the fault tree is a special tree-like logic diagram that graphically shows how the system fails (Purba, 2014). The input event of the logic gate is the "cause" and the output event is the "effect". Through layer-by-layer analysis of all influencing factors that may cause system failures, the logical relationship between equipment failures and various influencing factors is revealed. Therefore, the fault tree is similar to a system "snapshot" of a specific fault state (Ruijters & Stoelinga, 2015). It can not only reveal the various cause of system faults, display the weak links of the system, but also calculate the probability of each fault and evaluate each from different perspectives and evaluate the importance of each module from different perspectives.

The FTA method takes an undesired product failure event as the analysis target, and find all possible causes one by one from upwards to downwards, so as to calculate the logical relationship between various bottom events and top events that may exist in the analyzed system such as component failures, environmental influences, and human factors, and represented by an inverted tree diagram (Gusmao, Sliva, Poleto, Sliva & Costa, 2018). After building the fault tree, qualitatively analyze the combination method and combination path of each bottom event's impact on the top event, and quantitatively calculate the degree of such impact, and calculate the probability of causing the system failure that needs to be analyzed (Yeh & Simmons 2013).

4.1.2 Advantages and disadvantages of the FTA method

Fault tree analysis is often used at various stages such as system design, trial production and normal operation, and its characteristics are: simple, fast, convenient, image, etc. (Yao, 1989).

Advantages of FTA are:

1) Rather than being subject to a general reliability analysis of the analysis object, it is possible to analyze all its failure modes. It can not only analyze the effect of certain component failures on the analysis object, but also study the factors that cause the failure (Liu, 2003).

2) The graphics of the fault tree can well reflect the internal relationship of the system, and at the same time reveal the relationship between the component failure and the system failure, and discover the hidden dangers of the system (Guo, Qi & Li, 2018).

3) The FTA can not only conduct qualitative research on failure events, but also quantify the probability of occurrence of failure events, and apply first-hand data to safety assessment.

4) The fault tree analysis method can be programmed with software, which can build a more complete system.

Disadvantages of FTA are:

1) For larger or more complex system, the establishment of fault tree takes a longer time, which increase the difficulty of calculate (Ferdous, Khan, Veitch & Amyotte, 2009). Due to the large number of failures, it is necessary to establish fault tree by personnel with rich technical knowledge and strong analytical capability.

2) The FTA has a high requirement for data statistics, and the fault of each system needs to be analyzed separately.

4.1.3 Common terms and symbols of fault trees

Because the fault tree is presented through a graph, it is necessary to introduce some specific logical relationship gate symbols, event symbols, and basic terms to illustrate the logical relationship and causality between events and events. The establishment of a fault tree requires many symbols. For the research needs of this article, only events and their symbols and logic gates and their symbols are introduced.

The occurrence of conditions or actions is called events, which includes:

Top event: It is the result event of the joint action of all events. The top event is located at the top of the fault tree and is the target of fault analysis. It is always the output event of the logic gate in the fault tree in question rather than the input event.

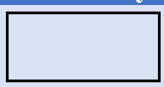
Intermediate event: It is the resultant event between bottom event and top event. The intermediate event is the output event of a certain logic gate, and at the same time the input event of other logic gates.

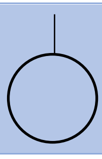
Bottom event: Located at the bottom of the fault tree, it is the influencing factor event that can only cause other events in the analysis method, and can only be used as the input event of the logic gate rather than the output event.

Basic event: The bottom event that does not need to be ascertained.

The symbols of each tape of event can be indicated as Table 3 shows.

Table 3 – Symbols of events

Symbols	Events
	Top event or intermediate event

	Bottom event or basic event

Source: Author

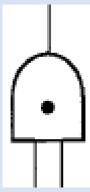
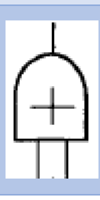
In fault analysis, logic gates describe logical causality between events.

AND gate: Indicates that the output event only occurs when all input events occur.

OR gate: Indicates that an output event occurs when at least one input event occurs.

The symbols of AND gate and OR gate can be indicated as table 4 shows.

Table 4 – Symbols of gates

Symbols	Gates
	AND gate
	OR gate

Source: Author

4.2 Steps of FTA method

The steps of the FTA method are to:

1) clarify the analysis scope of the system and top events;

2) build a fault tree;

3) simplified fault tree;

4) make a qualitative analysis of the fault tree;

5) make a quantitative analysis of the fault tree (Wang, 2012).

The specific analysis process is shown in Figure 14 bellow:

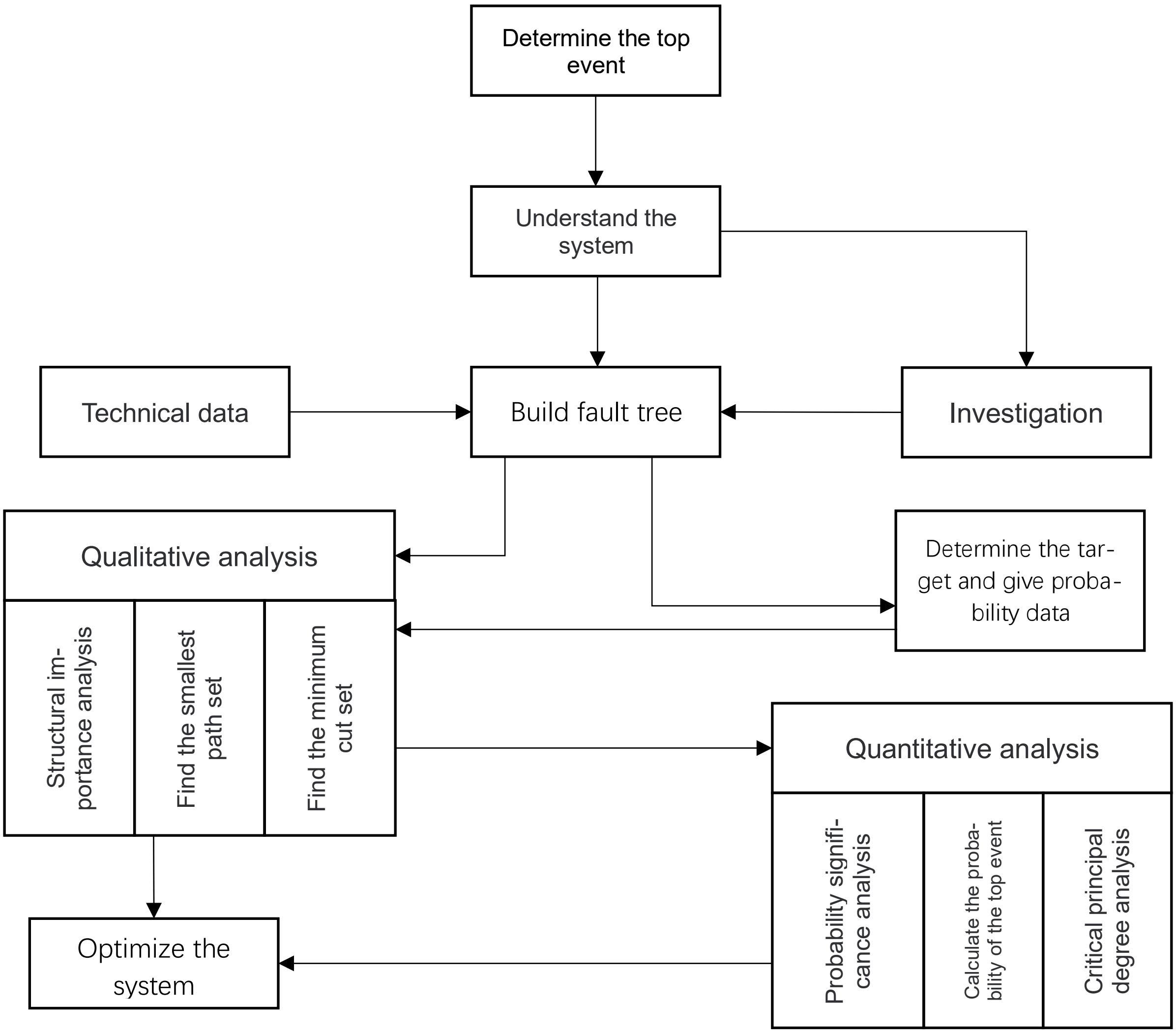


Figure 14 - Analysis process flow of FTA
Source: Author

4.2.1 How to build a fault tree

1) Be familiar with system failures

Before building the fault tree of the system, it is necessary for the builder to collect and sort out the data and actual running state of the system extensively (Torng & Jiun, 1997). At the same time, fully familiar with the structure of the system, what functions it has, what is the principle of operation, what are the forms of failure, and what are the causes of the failure (Yang, 2005). Only by mastering the basic data of the system, can the fault tree be established correctly and a reasonable fault analysis can be carried out.

2) Confirm the top event

How to distinguish which system events are regarded as top events is the core for establishing a fault tree. The builder can choose top events reasonably according to their different research perspectives and the perspective of solving practical problems.

When defining the top event, the concept should be clear, so that it is easy to find the direct cause of the top event, and use it for qualitative and quantitative analysis. When studying the failure of the system, if it is found that there are many unwanted events in the system, then multiple top events should be selected according to the principle of the system and multiple fault trees should be established for analysis.

3) Construct a fault tree

Starting from the top event, find out all possible direct causes of the events at all levels step by step, and use the corresponding symbols to indicate the events and their mutual logical relationship, until the bottom event is analyzed.

There are two methods of tree building: artificial tree building and computer aided tree building. Manual tree building is manual tree building, which requires a lot of work by analysts. Computer aided tree construction is the main method to solve the complexity of large system construction with the help of computer.

4) Fault tree normalization

In order to make a unified description and analysis of the fault tree, the constructed fault tree must be normalized into a fault tree containing only basic events, resultant events, AND gate, OR gate, and NOT gate.

5) Fault tree simplification

After establishing the fault tree, analyze the faults at all levels in turn, simplify the relationship between the faults, remove the impossible causes, phenomena and logical relationships, and then simplify the fault tree (Sun, Wei & Yu, 2002).

4.2.2 Qualitative analysis of the fault tree

Qualitative analysis is an important function of fault tree analysis. The main goal of qualitative analysis is to find the causes and combinations of causes that may lead to undesirable events related to the system by calculating the cut set and the minimum cut set. That is to find all the failure modes that lead to the occurrence of the top event, so that the diagnostic staff can find potential failures and design weaknesses to optimize the design, and propose feasible measures to enhance the safety factor of the system.

1) Cut set and minimum cut set

Cut set is a collection of several bottom events that cause the top event of the fault tree happen. The minimum cut set is the minimum bottom events that cause the top event of the fault tree to occur. It represents a failure mode that caused the top event of the fault tree happen.

For example, the sets that can make top events happen are:

{X1,}, {X2, X3}, {X1, X2 X3}, {X3, X4}, {X1, X4}

Since {X1} can directly cause the top event to occur, then {X1, X2 X3} and {X1, X4} are no longer the minimum set of bottom events that cause the top event happen.

Therefore, the minimum cut sets here are:

{X1,}, {X2, X3}, {X3, X4}

2) Ways to find the minimum cut set

The commonly used methods for finding the minimum cut set include the downlink method and the uplink method. The downlink method is used in the later calculation of this paper. The basic principle of the downlink method is: for each output event, if there is an OR gate below it, then each input event under the OR gate is lined up separately. If the following is an AND gate, then all input events under the AND gate are arranged in the same row.

The processes of the downlink method are: Starting from the top event, proceeding from top to bottom step by step, repeat the above principles for each resultant event until all the resultant events are processed, and the resulting set of bottom events in each row is a cut set of the fault tree. Finally, according to the definition of the minimum cut set, the cut sets of each row are compared in pairs, and those rows that are not the minimum cut set are crossed out, and the rest are all the minimum cut sets of the fault tree.

The following is an example to demonstrate the calculation of the minimum cut set:

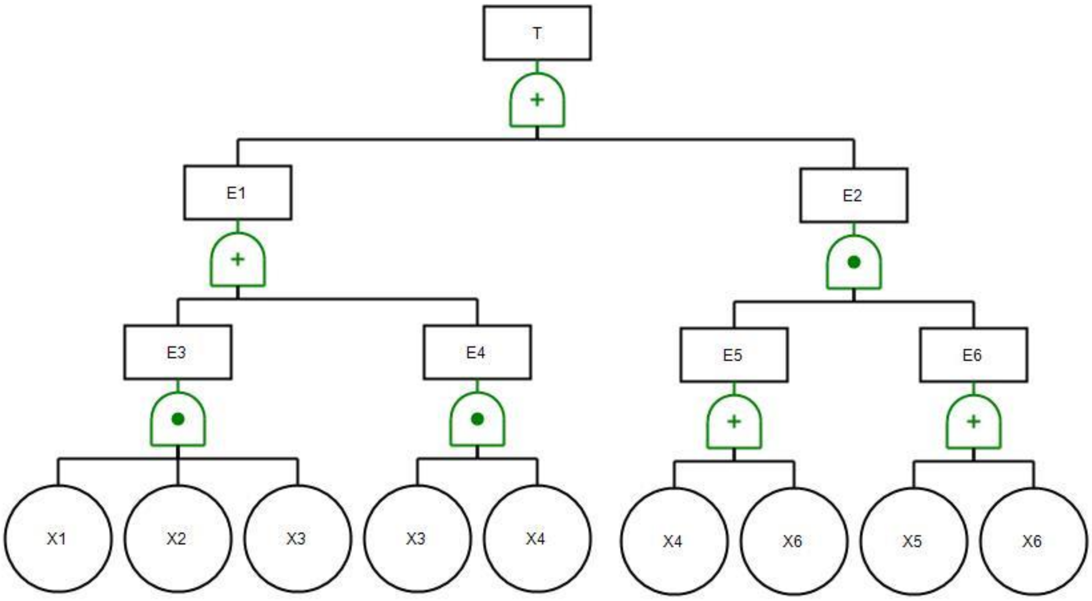


Figure 15 – An example of the fault tree
Source: Author

As for the fault tree given in Figure 15, the steps of downlink method can be shown in Table 5 bellow:

Table 5 – Steps of calculate minimum cut set use downlink method

Steps					
0	1	2	3	4	5
T	E_1 E_2	E_3 E_4 E_5E_6	$X_1X_2X_3$ X_3X_4 X_4E_6 X_6E_6	$X_1X_2X_3$ X_3X_4 X_4X_5 X_4X_6 X_6X_5 $X_6X_6=X_6$	$X_1X_2X_3$ X_3X_4 X_4X_5 X_6

Source: Author

Step 1: Below the top event T is an OR gate, then each input events E_1 and E_2 under the gate are arranged in a row.

Step 2: Below Event E_1 is the OR gate, then each input events E_3 and E_4 under the gate are arranged in a row; Below the event E_2 is the AND gate, then the input events E_5 and E_6 under this gate are arranged in the same row.

Step 3: Below Event E_3 is the AND gate, then the input events X_1, X_2 and X_3 under this gate are arranged in the same row; Below event E_4 is the AND gate, then the input events X_3 and X_4 under this gate are arranged in the same row; Below the event E_5 is an OR gate, then the input events X_4 and X_6 under the gate each arranged in a row and combined with the event E_6 to form X_4E_6 and X_6E_6.

Step 4: Below Event E_6 is an OR gate, then input events X_5 and X_6 under the gate each arranged in a row and combined with the event X_4 to form X_4X_5 and X_4X_6; Combine with event X_6 to form X_5X_6 and X_6X_6.

So far, all the resulting events of the fault tree have been processed. Each row obtained in step 4 is a cut set.

Step 5: Make a pairwise comparison. Since $\{X_6\}$ is a cut set, so $\{X_4, X_6\}$ and $\{X_5, X_6\}$ are not the minimum cut set and must be crossed out. Finally, all the minimum cut sets of the fault tree are:

$$\{X_6\},\ \{X_3,\ X_4\},\ \{X_4,\ X_5\},\ \{X_1,\ X_2,\ X_3\}$$

4.2.3 Quantitative analysis of the fault tree

The main purpose of quantitative analysis is to find the probability of the top event and other quantitative indicators, such as the structural importance, probability importance and relative probability importance of the bottom event when the probability of all bottom events is given.

For the fault tree shown in Figure 15, if all the bottom events are independent of each other, and the probability of each bottom event is as Table 6 shows:

Table 6 - Probability of each bottom event in Figure 15

q_1	q_2	q_3	q_4	q_5	q_6
0.02	0.02	0.03	0.025	0.025	0.01

Source: Author

1) Disjoint Boolean algebra method to find the probability of the occurrence of top events

As for the fault tree in Figure 15, the steps as followings:

1) According to the minimum cut sets calculated in 4.2.2, the top event can be expressed as the simplest Boolean expression of the sum of the bottom events:

$$T=X_6+X_3X_4+X_4X_5+X_1X_2X_3$$

2) Convert the above formula into disjoint Boolean sums:

$$T= X_6+X_3X_4\overline{X_6}+X_4X_5\overline{X_6}\,\overline{X_3}+X_1X_2X_3\overline{X_6}\,\overline{X_4}\,(\overline{X_4}+X_4\overline{X_5})$$
$$= X_6+X_3X_4\overline{X_6}+X_4X_5\overline{X_6}\,\overline{X_3}+X_1X_2X_3\overline{X_6}\,\overline{X_4}$$

$\overline{X_I}$ represents the opposite event of the bottom event X_i.

3) Calculate the probabilities at both ends of the disjointed expression in 2) to get the probability of the top event happening.

$$Q(q_1, q_2 \dots q_6) = P(X_6) + P(X_3X_4\overline{X_6}) + P(X_4X_5\overline{X_6}\,\overline{X_3}) + P(X_1X_2X_3\overline{X_6}\,\overline{X_4})$$
$$=q_6 + q_3q_4p_6 + q_4q_5p_6p_3 + q_1q_2q_3p_6p_4$$

Where $p_i = 1 - q_i$, which means the probability that the number i bottom event not occur. Bringing into the number to calculate, the probability of the top event occurring is:

$$Q = 0.011354$$

2) Structural importance of the basic event

The structure importance of the number i basic event is:

$$I\phi\,(i) = \frac{1}{2^{\,n-1}} \sum_{(x_{1,\dots},x_{i-1},x_{i-1},\dots,x_n)} [\, \phi(x_{1,}\dots, x_{i-1}, x_{i+1}, \dots, x_n - \phi(x_{1,}\dots, x_{i-1}, 0, x_{i+1}, \dots, x_n)]$$

i = 1, 2, …, n

Where ϕ（。）is the structure function of the fault tree, $\sum_{(x_{1,}\dots,x_{i-1},x_{i-1},\dots,x_n)}$ is the sum of all possibles where $X_1, X_2, \dots, X_{i-1}, X_{i+1}, \dots, X_n$ taking 0 or 1, respectively.

The importance of the basic event reflects the importance of each base event in the fault tree from the point of fault tree structure.

3) Probability importance of the basic event

The probability importance of the number i basic event is:

$$I_P\,(i) = \frac{\partial}{\partial q_i} Q\,(q_1, q_2, \dots, q_n)$$

i = 1,2, … , n

Where $Q\,(q_1, q_2, \dots, q_n)$ is the probability of the top event occurring. The probability importance of the number i basic event means the rate of change in the probability of the top event due to a small change in the probability of the number i basic event.

4) Relative probability importance of the basic event

The relative probability importance of the number i basic event is:

$$I_C\,(i) = \frac{q_i}{Q(q1,q2,\dots,qn)} \bullet \frac{\partial}{\partial q_i} Q\,(q_1, q_2, \dots, q_n)$$

i = 1,2, … , n

The relative probability importance of the number i basic event means the rate of relative change in the probability of occurrence of the top event due to a small relative change in the probability of occurrence of the number i basic event.

4.3 Fault tree analysis of ship failures for ships navigating in the CJK Fairway

According to the summary of the direct causes of the failures of ships in the CJK Fairway from 2015 to 2019 in Chapter 3, combined with the analysis of 895 cases to find out the deep-level causes of the failures, and establish models through fault tree theory to carry out qualitative analysis and quantitative analysis.

A fault tree drawing and analysis software FreeFat developed by Professor Meng Xianfei of China University of Mining and Technology is used in this dissertation to establishment, qualitative analysis and quantitative analysis of the fault tree. The software's qualitative analysis and quantitative analysis follow the classic algorithm described in 4.2. Because the fault tree in this article is quite large, the FreeFat software can not only ensure the accuracy of the calculation, but also save a lot of calculation process.

4.3.1 Determination of events

1) Define the top event

Ship failures in the CJK Fairway from 2015 to 2019 are the most important part of this paper. Therefore, ship failures in the CJK Fairway are defined as the top event of the fault tree.

2) Determination of intermediate events

The intermediate event is located between the bottom event and the top event, which is the cause of ship failures. According to the analysis in Chapter 3, select common fault types as the research object, and determine the intermediate events leading to the top event as: main engine failure, steering gear failure, cooling water system failure, black out and human factors.

3) Determination of basic events

Decomposing the cause of the main engine (ME) failure, the ME component failure, ME fuel system failure, ME cooling system failure, ME control system failure, and ME lubricating oil system failure are obtained. After further decomposing these faults, it is concluded that the basic events leading to the ME component failures are: exhaust valve fault, supercharger fault; basic evens lead to fuel system failures are: fuel injection pipe fracture, fuel injection pump fault, fuel injector block, fuel filter block; basic events lead to ME cooling system failures are: ME water pump fault, cylinder leakage; basic events lead to ME control system failures are: control circuit board fault, control air system fault; basic events lead to ME lubricating system failures are: ME lubricating filter blockage, no back up filter, lubricating oil mixed with impurities.

Decomposing the cause of the steering gear failure, the relevant basic events are: steering gear hydraulic oil leakage, steering gear hydraulic pump fault, rudder intertwine with rope, hydraulic control valve stuck.

Decomposing the cause of the cooling system failures, the relevant basic events are: seawater inlet filter blocked, cooling pipe damage, large quantities of air enter the cooling piping.

Decomposing the cause of the black out, the relevant basic events are: generator engine suddenly shut down, generator engine can't reset in short time.

Decomposing the cause of the human factor, the relevant basic events are: mis-operation, crew not familiar with the system, fatigue.

4.3.2 Develop the fault tree

According to the above established events and combined with the logical relationship between each event, connect all events by AND gate or OR gate. Using FreeFat software to develop a fault tree with the failure of the ship as the top event (see Figure 16).

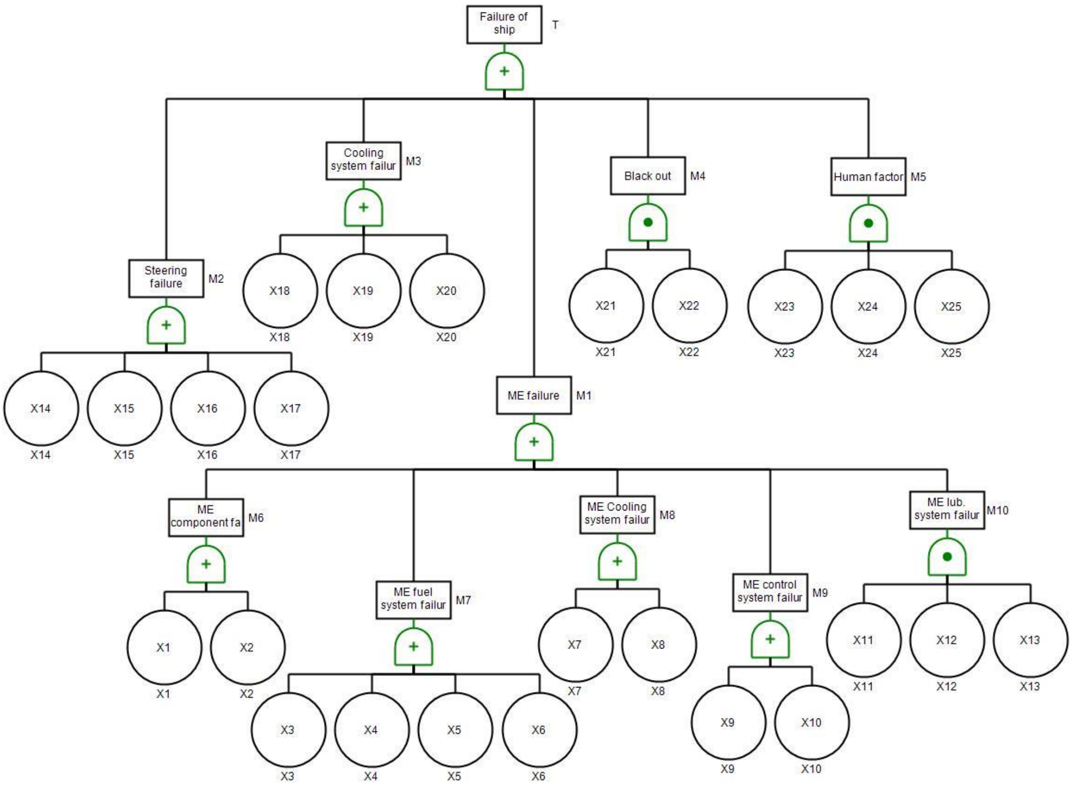


Figure 16 – Fault tree of ship failures for ships navigating in the CJK Fairway
Source: Author

The corresponding event code information in the fault tree is shown in Table 7 bellow:

Table 7 - Event code information

Event Code	Event Name	Event Code	Event Name
T	Ship failures for ships navigating in the CJK Fairway	X8	ME cylinder leakage
M1	ME failure	X9	ME control circuit board fault
M2	Steering gear failure	X10	ME control air system fault
M3	Cooling system failure	X11	ME lubricating filter block
M4	Black out	X12	No back up filter

M5	Human factor	X13	Lubricating oil mixed with impurities
M6	ME component failure	X14	Steering gear hydraulic oil leakage
M7	ME fuel system failure	X15	Steering gear hydraulic pump fault
M8	ME cooling system failure	X16	Rudder intertwine with rope
M9	ME control system failure	X17	Hydraulic control valve stuck
M10	ME lubricating oil system failure	X18	Seawater inlet filter blocked
X1	ME exhaust valve fault	X19	Cooling pipe damage
X2	ME supercharger fault	X20	Large quantities of air enter the cooling piping
X3	ME fuel injection pipe fracture	X21	Generator engine suddenly shut down
X4	ME fuel injection pump fault	X22	Generator engine can't reset in short time
X5	ME fuel injector blockage	X23	Mis-operation
X6	ME fuel filter blockage	X24	Crew not familiar with the system
X7	ME water pump fault	X25	Fatigue

Source: Author

4.3.3 Qualitative analysis of the ship failure fault tree

Through making qualitative analysis, we can find the influencing factors and the combination of influencing factors that lead to the occurrence of top events, and find the weak links in the system, so as to provide targeted opinions on improving design or management. Qualitative analysis is one of the important roles of fault tree theory.

Through using the FreeFat software and using downlink method, 20 minimum cut sets of the fault tree can be obtained as below:

(X1), (X10), (X11*X12*X13), (X14), (X15), (X16), (X17), (X18), (X19), (X2), (X20), (X21*X22), (X23*X24*X25), (X3), (X4), (X5), (X6), (X7), (X8), (X9).

Looking at the above minimum cut sets, it can be found that most of the minimum cut sets consist of only one single basic event. This is due to the large number of ship systems and the large number of key equipment on board. Although some safety redundancy has been made in the design of ships from the perspective of safety, the failure of a small part of a system will still cause the whole ship to lose control. This partly reflects the vulnerability of ships to safe operation.

At the same time, it can be found that the minimum cut set that consists of a single event is the basic event of the main engine failure, steering gear failure and cooling water failure. In other words, in these systems, the occurrence of a single basic event can directly lead to the occurrence of a top event.

4.3.4 Quantitative analysis of the ship failure fault tree

1) The determination of the probability of each basic event

The probability of basic event occurrence is the basis of qualitative analysis of fault tree. However, for the 25 basic events in this paper's fault tree, it is difficult to accurately determine their probability of occurrence. On the one hand, the situation of each ship cannot be same, on the other hand, it is impossible to collect such a huge amount of data.

As a solution, the author communicated with experienced experts in the industry, and asked them to estimate the probability of each basic event through a questionnaire survey, and then weighted the average. In order to make the estimation more accurate, the author distributed questionnaires to 10 experts engaged in different fields (see

Annex 1), which are: 1 PSCO from Shanghai MSA, 7 ocean-going ship chief engineers from different ships, 1 field surveyor and 1 mechanical supervisor from shipping company.

All the 10 questionnaires were recovered and the data were valid. The weighted average of the occurrence probability of each basic event was shown in Table 8.

Table 8 - Probability of each basic event by questionnaire

Event Code	Probability	Event Code	Probability
X1	0.001	X14	0.003
X2	0.001	X15	0.002
X3	0.002	X16	0.002
X4	0.006	X17	0.003
X5	0.015	X18	0.007
X6	0.004	X19	0.005
X7	0.002	X20	0.004
X8	0.005	X21	0.003
X9	0.001	X22	0.01
X10	0.002	X23	0.05
X11	0.002	X24	0.05
X12	0.02	X25	0.01
X13	0.005		

Source: Author

2) Structure importance analysis

According to FreeFat's calculation of the logic structure of the fault tree, the structural importance of the basic event is as follows:

I(X20)=I(X19)=I(X18)=I(X17)=I(X16)=I(X15)=I(X14)=I(X10)=I(X9)=I(X8)=I(X7) =I(X6)=I(X5)=I(X4)=I(X3)=I(X2)=I(X1)>I(X22)=I(X21)>I(X25)=I(X24)=I(X23)=I (X13)=I(X12)=I(X11)

Through the structural importance analysis, it can be found that among the bottom events that may lead to the occurrence of the top event, the bottom events involving main engine failure, steering gear failure and cooling water system failure have greater structural importance. This is consistent with the proportion of fault categories.

3) Probability importance analysis

After entering the occurrence probability of each basic event into FreeFat, the probability importance of the basic event can be obtained as shown in Table 9.

Table 9 - Probability importance of each basic event

Ranking	Probability importance	Ranking	Probability importance
1	X1(0.93774)	14	X15(0.92553)
2	X5(0.93774)	15	X16(0.92553)
3	X18(0.9301)	16	X2(0.924607)
4	X4(0.92925)	17	X9(0.924607)
5	X19(0.9283)	18	X21(0.00923)
6	X8(0.92832)	19	X22(0.00277)
7	X6(0.92739)	20	X25(0.00230)
8	X20(0.9273)	21	X23(0.00046)
9	X14(0.9264)	22	X24(0.00046)
10	X17(0.926)	23	X11(0.00009)
11	X3(0.9255)	24	X13(0.00003)
12	X7(0.9255)	25	X12(0.00002)
13	X10(0.925)		

Source: Author

The probability importance analysis results are consistent with the structural importance, showing that the basic events of the main engine failure, steering engine failure and cooling water failure have more than 90% probability for directly causing ship failures.

4) Relative probability importance analysis

After entering the occurrence probability of each basic event into FreeFat, the relative probability importance of each basic event can be obtained as shown in Table 10.

Table 10 - Relative probability importance of each basic event

Ranking	Relative probability importance	Ranking	Relative probability importance
1	X1(0.18431)	14	X15(0.02425)
2	X5(0.18431)	15	X16(0.02425)
3	X18(0.08531)	16	X2(0.01211)
4	X4(0.07305)	17	X9(0.01211)
5	X19(0.06082	18	X22(0.00036)
6	X8(0.06082)	19	X21(0.00036)
7	X6(0.04860)	20	X23(0.00030)
8	X20(0.04860)	21	X24(0.00030)
9	X14(0.03641)	22	X25(0.00030)
10	X17(0.03641)	23	X12(0.00001)
11	X3(0.02425)	24	X13(0.00001)
12	X7(0.02425)	25	X11(0.00001)
13	X10(0.02425)		

Source: Author

Through the relative probability importance analysis, it can be found that the probability of ship failures can be effectively reduced by reducing the main engine failure.

CHAPTER 5 RECOMMENDATIONS AND CHALLENGES IN THE FUTURE

5.1 Recommendations

As the ship equipment work under the conditions of high temperature, humidity, vibration, and even bad weather for a long time, they are prone to all kinds of faults.

In addition, the complex hydrologic and navigation characteristics of the CJK Fairway further increases the possibility of failure. If a ship failure while sailing in the open ocean, there will be enough time and space to repair it, but in the CJK Fairway with dense ships and narrow waterways, if the ship breaks down and causes operation restrictions or even out of control, it will easily lead to grounding, collisions and even oil spills.

According to the above analysis, there are certain rules to follow in the failure of vessels in CJK Fairway. First of all, the main engine failure, steering gear failure and cooling water system failure are the most common failure types. Secondly, the probability of ship failure is higher in the high temperature season.

According to the investigation and analysis after the accident, a large proportion of the failures could have been avoided, either because the ship maintenance was not in place, or the crew's emergency response was not timely, leading to a small fault that eventually led to the loss of control of the whole ship. Therefore, based on the above analysis, the author puts forward corresponding recommendations to vessels, management companies and competent authorities in order to reduce the failure rate of vessels navigating in the CJK Fairway.

4.1.1 For ship management companies

The ship management companies should carry out the main responsibility of ship safety management and create a good safety culture atmosphere in the fleet. Firstly, the management companies should ensure that there are sufficient resources on board, such as personnel, spare parts and food. It is not reasonable to reduce ship manning, spare parts inventory, and extend ship maintenance schedule in consideration of excessive cost savings. The ship should be docked on time according to the planned time frame. Secondly, the management companies should supervise the implementation of the Safety Management System (SMS) on board ships. Effective implementation of the SMS should be strengthened by strengthening crew training before new crew members on board the ship and enhance port inspection.

For ships navigating in the CJK Fairway, they should be informed the hydrological characteristics, navigation characteristics and local requirements in advance, so that the ship could be prepared in advance to ensure the ship in a good condition. Ships with excellent safety operating records should be rewarded to increase the motivation and sense of honor of the crew.

4.1.2 For ships navigating in the CJK Fairway

According to Article 4 of the "CJK Deepwater Channel Navigation Safety Management Measures", revised and implemented by the Shanghai MSA on September 1, 2019, "Vessels intending to enter deep water channels shall be tested in advance on main engine, steering gear, communications and emergency equipment, etc., and ensure that they are in good technical condition" (Shanghai MSA, 2019).

Vessels shall be inspected in advance in accordance with the prescribed article, especially the main engine systems, steering gear and cooling water systems, and any faults shall be solved before entering the fairway. Because by the statistics and FTA, theses system more likely failure in the CJK Fairway during sailing. In normal operation, the crew shall maintain the ship's equipment on time according to the maintenance plan to ensure the smooth operation of the SMS.

If a ship breaks down in the channel, the ship should report to Wusong VTS center in time so that VTS can organize emergency response and avoid secondary accidents.

4.1.3 Supervision measures for the competent maritime authority

As for Shanghai MSA, the competent authority for navigating vessels in CJK Fairway, the author suggests strengthening the management from the following aspects.

1) Strengthen supervision of shipping companies

For shipping companies whose Document of Competence (DOC) certificate are issued by Shanghai MSA, the Shanghai MSA can conduct targeted inspections when conducting external audits of the shipping companies every year. Before the audit, the auditors can check whether the company's ship has failure records in the CJK Fairway in the past two years. During the audit they can focus on the company's SMS relate to handing procedures of ship failures by looking through relevant records, and verifying whether the SMS was implemented. In this way, shipping companies are urged to implement their main responsibilities and improve their fleet management level.

2) Strengthen the on-site inspection of ship failures

In order to curb the rapid increase in the number of ship failures in the CJK Fairway, Shanghai MSA issued a regulation in April 2019 to carry out 100% inspection of vessels with electromechanical failures in the fairway and 100% detention of vessels with serious deficiencies found in the inspection. In 2019, the detention rate of PSC inspection carried out by Shanghai MSA was 8.4%, which was not only the highest in all years, but also 2.7 times higher than the average detention rate of 3.13% in Tokyo Memorandum (MOU) region (Tokyo MOU annual report, 2019).

It is suggested that when PSC or FSC inspection is carried out on the failure ships, detailed inspection should be carried out around the equipment with fault to confirm whether it has returned to normal state. At the same time, confirm the cause of the accident, determine whether there is responsibility for ship safety management, whether there are human errors, and issue specific deficiencies in the inspection report. In addition, the ship’s daily maintenance records, personnel training records, and related drill records should be inspected, the overall environment and condition of the engine room should be assessed, and the ship’s problems in the management of the ship’s machinery should be pointed out by officer and rectification should be supervised.

In the daily PSC or FSC inspection, the maritime authority officers should pay more attention on the equipment easy to lead ship failures, such as main engine system, steering gear system and cooling water system. If related deficiencies are found by PSCOs or FSCOs, the ship should rectify them before departure.

3) Strengthen the operational inspection of seafarers

In order to reduce the failures caused by human factors, the competent authority should carry out the seafarer's operational inspections according to the common types of failures in CJK Fairway during the inspection. The crew is required to be proficient in operating the ship's machinery and equipment within the responsibility to reduce ship failures caused by the crew's mis-operation or human error.

4) Continue to collect data to provide support for innovation in regulatory measures

In addition, it is necessary to continue collecting and sorting out the information of failure ships, requiring the failure ships to provide more abundant and standardized information reports, and establishing a database of ships that frequently failures in the fairway, so that the competent authority can formulate a more scientific and targeted management system.

5.2 Challenges in the future

Looking forward to the future, there are many factors affecting the safe operation of ships. In view of the impact of new technology and COVID-19, this dissertation proposes the possible impact on ship failures.

5.2.1 New technologies and human error

Driven by new technologies, more and more new equipment or systems are being used on ships. However, these applications are mostly aimed at saving ship operating costs, and the systems generated by new technologies are often more complex. Once fault occurs, the service provider often needs to be asked for help because the crew are difficult to eliminate the fault.

A perception of technology as fully reliable and trustful, can lead to underestimating risks and consequently to the change of attitude toward seamanship practices and procedures (Toni, Nermin & Jelena, 2017), According to Schröder (2012) states, “new technology may often create a false sense of confidence, and thereby lead to an increase in the acceptance of risks”.

Therefore, contrary to popular belief, higher levels of automation mean higher safety, “technology can contribute to the occurrence of accidents caused by human error and hence defeat the purpose for which it was introduced” (Lutzhoft & Dekker, 2002). The ever-increasing functions and high degree of autonomy of automation systems pose challenges for monitoring, integrating and interpreting the information provided by automation.

No matter how new technologies in shipping are developed in the future, humans are still the ship's controllers, and the competence of the crew is still the decisive factor in determining the safety of the ship. If seafarers rely too much on new technology, ship failures will not decrease in the future.

5.2.2 The impact of COVID-19 to ship failures

Since the outbreak of COVID-19 in early 2020, shipping and crew members have suffered a huge impact due to the characteristics of ships' international navigation.

For ocean-going ships, surveyors and PSCOs are more cautious about contact with crew on board. In fact, after the outbreak of the COVID-19, many local governments have not allowed surveyors and PSCOs to board ships from abroad. A large number of ship survey dates have been postponed for half a year or even longer, and PSC inspection volumes in various ports have also dropped significantly.

On 12 March, 2020, TOKYO MOU Secretariat issued Circular latter NO. 2020-2 to its member states that the Secretariat had permitted ships' surveys and valid of certificates exceeded no more than 3 months due to the impact of COVID-19 (TOKYO MOU, 2020). And on 2 June, 2020, the IMO issued Circular latter NO. 4204/Add.19 that the Administration could extend the period of validity of a certificate for no more than 3 months (IMO, 2020). This makes the ship lack important safety barriers like survey and PSC, which is not conducive to maintaining a safe state.

For crew members, many ports have banned them from disembarkation as a precaution against COVID-19, leaving them unable to change shifts as planned. According to IMO news, as of September 14, more than 300,000 seafarers cannot be repatriated, and those on board have had their contracts extended, sometimes beyond 17 months (IMO, 2020). Travel restrictions imposed by governments around the world have created significant hurdles to crew changes and repatriation of seafarers, which has led to a growing humanitarian crisis as well as significant concerns for the safety of seafarers and shipping (IMO, 2020).

A large number of crew members have overdue service on the ship, which is extremely unfavorable to the crew's mental state, and is more prone to fatigue and excessive mental stress. In this state, human errors will increase significantly, and ship failures are more likely to occur.

CHAPTER 6 CONCLUSION

As the CJK Fairway is located at the mouth of the Yangtze River, its hydrological characteristics are relatively complex and changeable, which brings certain difficulties to ship navigation. In addition, the CJK Fairway is densely navigable throughout the year and there are many meeting points for ships. Ships navigating in the CJK Fairway needs to frequently change the main engine load and course to keep the ship on a safe route. This increases the probability of ship failures in the CJK Fairway.

By analyzing the ship failure information collected by Wusong MSA in 2018 and 2019, main engine failures accounted for the highest proportion of all failure types. Other common failure types include steering gear failure, cooling water system failure, and black, etc. Through the fault tree analysis method, it is also found that the main engine failure has the greatest probability lead to the ship failure, which is consistent with the actual data.

However, in quantitative analysis, because the probability of occurrence of each basic event is difficult to accurately calculate, the author invited experts to estimate, which is subjective.

Ship failures are very harmful to the environment and navigation safety of the Yangtze River estuary areas and require the joint efforts of all departments of the entire industry. Although the future will face the challenges from new technologies and COVID-19 epidemic, as long as the ship management companies, ships and competent authority do their own work well, the probability of ship failures in the CJK Fairway will be decreased.

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Appendix 1

Questionnaire

Dear experts, thank you for taking the time to participate in this questionnaire survey. Please make an assessment of the probability of the following events occurring while the ship is sailing in the CJK Fairway based on your work experience and knowledge.

Event Code	**Event Name**	**Probability of failure happen**
X1	ME exhaust valve fault	
X2	ME supercharger fault	
X3	ME fuel injection pipe fracture	
X4	ME fuel injection pump fault	
X5	ME fuel injector blockage	
X6	ME fuel filter blockage	
X7	ME water pump fault	
X8	ME cylinder leakage	
X9	ME control circuit board fault	
X10	ME control air system fault	
X11	ME lubricating filter block	
X12	No back up filter	

X13	Lubricating oil mixed with impurities	
X14	Steering gear hydraulic oil leakage	
X15	Steering gear hydraulic pump fault	
X16	Rudder intertwine with rope	
X17	Hydraulic control valve stuck	
X18	Seawater inlet filter blocked	
X19	Cooling pipe damage	
X20	Large quantities of air enter the cooling piping	
X21	Generator engine suddenly shut down	
X22	Generator engine can’t reset in short time	
X23	Mis-operation	
X24	Crew not familiar with the system	
X25	Fatigue	

Your professional identity is: ____

Thank you again for taking the time to participate in this survey. Wish you all the best!