FAILURE ANALYSIS AND RISK ASSESSMENT OF MOORING SYSTEMS

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A PROJECT SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING, FACULTY OF ENGINEERING, UNIVERSITY OF BENIN, EDO STATE, NIGERIA.

IN COMPLETE FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF BACHELOR OF ENGINEERING (B.ENG) DEGREE IN MARINE ENGINEERING.

NOVEMBER, 2025

CERTIFICATION

This is to certify the research, Failure Analysis and Risk Assessment of Mooring Systems, was carried out by

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DEDICATION

This research paper is dedicated to God Almighty for his guidance, strength, blessing and his grace upon us to carry out this project. To our supportive parents and families who fueled our passions for learning during the course of our academic pursuit. They provided us with a profound sense of enthusiasm and perseverance in continuing this research.

Moreover, we dedicate this work to our supervisor, Engr. Martin Osikhuemhe, who constantly aided is with the assistance needed for the success of this project

ACKNOWLEDGEMENTS

First and foremost, we want to give thanks to God Almighty for strength and wisdom throughout this project.

Our sincere gratitude goes to our wonderful and highly esteemed supervisor Engr Martin Osikhuemhe for his contribution, time, disciplinary actions and continuous encouragement. His guidance played a vital role in shaping the quality and direction of this work. Our gratitude also extends to all the lecturers in the Department of Mechanical Engineering for the knowledge, discipline, and academic foundation they have provided over the years.

We also express our heartfelt appreciation to our Parents Mr and Mrs Ikuku and Mr and Mrs Eghaghe for their prayers, sacrifices, and unwavering support. Their constant encouragement has kept us focused and motivated. Our course mates and friends equally deserve recognition for their assistance, discussions, and cooperation during the development of this project.

Finally, we are thankful to all the marine professionals who took the time to respond to our questionnaire. Their valuable insights and experiences significantly contributed to the success of this study.

ABSTRACT

Mooring systems remain one of the most critical safety components in marine operations, yet failures continue to occur across ports and offshore environments. These failures often lead to equipment damage, operational disruptions, and, in severe cases, loss of life. This study investigates the major causes of mooring system failures and evaluates the associated risks, with a particular focus on mooring practices in port environments. The research combines a detailed review of mooring system fundamentals with an assessment of human, environmental, and equipment-related factors that influence failure. A structured questionnaire was used to obtain first-hand information from marine professionals, and the responses were analysed using the Failure Mode and Effects Analysis (FMEA) technique.

The findings reveal that human error, inadequate inspection routines, worn mooring lines, and environmental forces such as strong winds and currents are leading contributors to mooring failures. Several failure modes were identified, but the highest Risk Priority Numbers (RPNs) were associated with poor maintenance culture, deviation from safety procedures, and the use of degraded lines. These areas represent the most urgent risks requiring intervention. The study also highlights gaps in compliance with standard mooring system management practices, including inconsistent adherence to the Mooring System Management Plan (MSMP).

Based on the results, the research recommends stricter enforcement of mooring safety procedures, regular condition monitoring of mooring equipment, improved crew training, and the adoption of structured risk-assessment tools such as FMEA during operations. Strengthening these areas will significantly reduce the likelihood of failures and enhance the overall safety and reliability of mooring operations in Nigerian port environments.

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CHAPTER ONE
INTRODUCTION

1.1 Background to the Study

The maritime sector transports over 80% of the world's cargo, making it a vital component of global trade (UNCTAD, 2023). Because mooring operations ensure that ships may land safely and securely in various port settings, they are an essential component of this vast network. The components of a mooring system include lines, anchors, winches, capstans, bollards, cleats and fairleads, among others (OCIMF, 2018). These components cooperate to maintain a boat's stability in the face of shifting external factors such as wind, currents, surges, waves, and swells. The efficient operation of these systems is essential for the safety of the ship, its crew, and the port infrastructure surrounding it. In addition to being crucial for both design and operation, mooring systems are also prone to failure in a variety of ways. The material's physical defects and wear, fatigue damage, abrasion, and corrosion are examples of progressive degradation mechanisms. A significant contributing factor to line breakages is external influences, particularly excessive stress brought on by unfavourable weather conditions like strong winds and unstable seas.

The maritime sector is constantly working to reduce risks and make things safer through several classification societies and international agencies, like the International Maritime Organisation (IMO). The IMO's new guidelines, including MSC.1/Circ. 1619, 1620, and 1175/Rev.1, outline the new standards for designing, inspecting, and maintaining mooring equipment and arrangements (IMO, 2020a; IMO, 2020b). Classification societies, such as Lloyd's Register (LR) and the American Bureau of Shipping (ABS), are crucial for establishing and upholding strict technical requirements for the construction and operation of ships and offshore installations (Lloyd's Register, 2023; ABS, 2023). These guidelines cover specifications for chains used for anchoring offshore as well as guidelines for single-point moorings.

Seaports are vital to a nation's economy since they serve as major hubs for coastal and international trade and significantly enhance the movement of products and services between various economic sectors. For Nigeria's marine sector, the most significant government organisation is the Nigerian Maritime Administration and Safety Agency (NIMASA). The

marine sector in Nigeria is constantly expanding, which implies that shipping operations and tonnage are rising as well. For Nigerian seaports, however, this expansion is accompanied by numerous operational and infrastructure issues. Overcrowding of ships, inadequate port facilities, sluggish procedures, and ships that take too long to turn around are some of these issues. Mooring operations in Nigerian ports are more risky due to increased maritime traffic and issues with infrastructure and operations. Long turnaround times and heavy traffic can burden the personnel and equipment, increasing the likelihood of errors or equipment failure. The accompanying diagram illustrates a highly stressed system where operational issues increase the likelihood of mooring failure.

1.2 Statement of the Problem.

As the need for offshore structures increases, determining the causes of mooring system failures is a significant and persistent issue in the worldwide maritime sector that has detrimental impacts on the environment, economy, and safety. Despite ongoing improvements in safety measures and the implementation of international regulations, accidents continue to occur far too frequently. Approximately 300 people worldwide lose their lives in mooring-related accidents each year, with ropes and wires directly responsible for an astounding 95% of these fatalities (Frydenberg & Bergan, 2019). Additionally, 60% of all injuries during mooring operations occur while the boat is actively berthing or unberthing (UK P&I Club, 2019).

Despite frequent rule changes, the significant injury and fatality rates indicate that mooring failure is a general issue that cannot be resolved by improved technology or regulations alone. Because human conduct, environmental changes (such as high wind gusts), and equipment limits interact in complex ways, "snap-back zones" are always risky. Due to operational inefficiencies (such as traffic and lengthy turnaround times), infrastructure issues (both digital and physical), and potential weaknesses in regulatory enforcement, mooring operations in seaports are challenging.

1.3 Aim and Objectives

A comprehensive analysis of mooring system failures and the hazards they pose to commercial ships in seaports is the aim of this project.

Objectives

I. To determine the most frequent causes of commercial ship mooring system failures in seaports and classify them.
II. To assess how mooring system failures affect the seaport system's safety, economy, and ecology.
III. To evaluate the current national and international regulatory frameworks and risk assessment techniques used in mooring operations at seaports.
IV. To make recommendations for improved methods of evaluating and lowering risks that are associated with mooring operations.

1.4 Significance of the Study

This work is important for improving the efficiency and safety of seaports. An analysis of mooring system failures in the local and international context provides useful information for improving risk management, reducing costly delays, and preventing accidents. Through the completion of enforcement and infrastructure deficiencies, the findings can assist NIMASA and NPA, two significant regulatory agencies (in Nigeria), etc., in modifying their policies. Better port performance, reduced operating expenses, and safer working conditions will benefit a variety of stakeholders, including shipping companies, port operators, and seafarers. The study also benefits the marine industry by reducing resource loss, pollution, and accidents, which boosts the country's economy and safeguards the environment.

1.5 Scope of the Study

The investigation of mooring system failures and the dangers they pose during commercial vessel berthing, unberthing, and alongside operations in seaports is the focus of this study. While reviewing relevant national and international regulations.

CHAPTER TWO
LITERATURE REVIEW

2.1 Fundamentals of Mooring Systems

The fundamentals of mooring systems are as follows:

2.1.1 Definition and Purpose of Mooring

Mooring is the process of tying a boat to a fixed or floating structure so that it stays connected while the port is busy with operations such as the loading and unloading of a ship. The main job of the mooring system is to keep the ship safe from winds, waves, and currents so that it stays in the right place and direction. Strong mooring systems are essential because they keep the ship, its crew, and the environment safe while also letting the ship operate safely at the berth or in offshore locations. There are many different ways to moor ships in the maritime industry, including ship-to-ship transfer, single-point or single-buoy mooring, conventional or multi-buoy mooring, Baltic mooring, Mediterranean mooring, and anchor mooring. Each method is tailored to suit the specific requirements of various vessels, cargo operations, and environmental conditions. For instance, the single-point mooring is mostly used to move liquid or gas cargo from big ships in ports lacking special equipment (Das et.al., 2015). This process needs favourable weather. This variety shows that mooring is not a simple process; the type of vessel, the type of cargo, and the port's infrastructure all have a big impact on how complicated and specific the process is.

2.1.2 Mooring System Components

A mooring system is strong and works well because it has many parts that work together. Each part has a specific job and must deal with various stressors.

The system is made up of many parts that are connected to each other and must do their jobs while dealing with different forces that try to break or damage them.

2.1.2.1 Mooring Configuration

To keep them stable and able to stay in the water, many mooring systems are put on floating platforms. Catenary and taut systems are two types of mooring systems that are often used in the industry. The type of configuration that is best for the platform will depend on the type of line material used and the type of anchor. For example, the catenary system is used with the drag embedment anchor when horizontal load is present, but the taut system is used with the vertical load anchor or the pile suction anchor. (American Petroleum Institute, 2005).

2.1.2.2 Catenary System

A catenary mooring system is a simple type of slack mooring. The system is made up of steel chains, which may also have steel wire or synthetic rope sections. It hangs freely between the floating structure and the anchor, making a catenary shape. The system's slack lets the anchored structure move up and down and side to side. The top part of the mooring line may be made of chain and wires or synthetic ropes. The bottom part of the line, on the other hand, lies on the seabed, which makes it bigger. This made the weight next to the anchor work as a counterweight. Compared to a taut-leg mooring system, this one is not too hard to set up.

This system is most often used in shallower waters because, as the water gets deeper and the vertical distance and demand for the catenary slack in the mooring line increase, more chain and wires are needed along the horizontal axis. The catenary system becomes less cost-effective because the total length increase leads to higher costs.

2.1.2.3 Taut-Leg System

Mooring lines that are pre-tensioned until they are taut make up a taut-leg mooring system. This system uses taut moorings to keep a floating structure stable, which is not something that is usually built into the structure's design. The taut mooring has a small footprint and is stable, but the mooring line is hard to set up and costs a lot of money. A taut-leg mooring system keeps the anchored structure from moving up or down. Each mooring line is also very important for keeping the structure stable. If one line fails, the system could become very unstable. Also, tensioned mooring lines are more likely to get worn out than catenary systems. The taut systems have the benefit of covering a much smaller area on the seabed than the catenary system (Lingzhi X. et al., 2020). The platform can't move up and down once the taut system is in place.

As the load gets heavier, an anchor that can handle the big forces that are created is needed (N. Baltroo, 1998).

2.1.2.4 Semi-Taut System

The semi-taut system is a mix of the taut mooring system and the catenary mooring system. This system lets the structure move up and down and side to side, which cuts down on fatigue loading and makes mooring lengths shorter than a catenary system. But the fact that the floating structure can move around makes it less stable, so some of this will have to be taken into account when designing the structure. The semi-taut and taut systems are better for deep-water use than the catenary system because they cost less.

This is because they both have shorter mooring lines and don't need as much space on the seafloor as the catenary system. The shorter mooring lines save money on materials, so they are lighter and cheaper to use in deeper water.

2.1.2.5 Anchors

Anchors are metal devices that hold a ship or floating platform to the seabed so that it doesn't drift because of the environmental load conditions it is in. Anchors are very important because they can hold things in place by either hooking into the seabed or by their weight. You can also use a combination of both. Most ships and floating platforms choose their anchors based on how much weight and size they need to hold and the texture of the seabed (Shengjie R., et al., 2024). Different kinds of anchors include the following :&? (

I. **Deadweight anchors:** These are the simplest type of anchor. They are mainly used to resist horizontal and vertical forces caused by the load. The anchor's weight and how much it rubs against the seabed determine how much it can hold. Steel and concrete are used to make these deadweight anchors. They are easy to make and cheap, so they can be used in any type of seabed or loading situation.

II. **Drag Embedment Anchors:** These are the most common type of anchor used for mooring. The drag embedment anchor is the most popular type of anchoring system on the market right now. DEA anchors are made to go all the way or partway into the seabed, and the soil resistance in front of the anchor helps keep the platform in place. These

anchors are great for horizontal loads but not for vertical loads because they don't work as they should. (R. Ruined, 2003).

III. **Vertical Load Anchors:** This group of anchors has driven pile/suction anchors, special vertical load anchors, and the drilled & grout anchor. Suction piles are the best anchors for building in deep water. The tubular piles go into the seabed, and a pump pulls the water out and anchors the anchor deeper into the seabed. You can use the suction pile on different types of seabeds, like sand, clay, or mud. The driven pile is also useful in a lot of different seabed conditions. Compared to the cost of installation, the cost of these vertical load anchors is relatively low. They are efficient and long-lasting, but they are also expensive. These anchors are often used with TLPs to hold boats in place. Most vertical load anchors need to be drilled and hammered in to be put in place. This makes a lot of noise underwater, which should be seen as a risk that people agree to, especially in places with a lot of marine life (Shengjie R., et al., 2024).

2.1.2.6 Mooring Lines

The most crucial components of the mooring system are the mooring lines. The ship is secured to the mooring point by these primary tethers or harnesses. Boats and stationary objects like docks, buoys, and anchors are connected by mooring lines (IMO, MSC.1/Circ.1619). Synthetic fibres like polyester and polypropylene, chain and wire ropes, and more sophisticated and high-performance materials like Ultra High Molecular Weight Polyethene (UHMWPE), better known by brand names like Dyneema® or Spectra®, are examples of common materials. The way ships tie up and anchor has been altered by rope materials. Similar to Dyneema, UHMWPE is lightweight, long-lasting, and has a low stretch. Important military ships and ocean platforms benefit greatly from its protection from friction, the sun, chemicals, and marine life (S.D. Weller et al., 2015). Nylon rope is popular because it is robust, stretches easily, and absorbs shock from waves. When things change quickly, it performs well. Although it doesn't stretch as much and is more resilient to sunlight, polyester rope is just as robust as nylon. For boats that remain in one location for months or years, this makes it ideal.

The OCIMFS Meg4 standards are very strict when it comes to selecting the proper mooring lines. The most crucial metric is the ship design minimum breaking load (SDMBL), which indicates

the strength requirements for all mooring components. Additionally, every ship must have a line management plan that instructs the crew on how to inspect, maintain, and swap out their mooring equipment. The strategy differs according to the ship's kind, destination, and frequency of dockings. You should also consider the type of ship that will use the line and the amount of weight it can support for each unit. If it is compatible with the ship's current mooring system, how frequently it will be used, how well it can withstand being squeezed, and what kind of weather it will encounter.

2.1.2.7 Chains

Chains are used for a lot of things, like mooring systems and keeping platforms in place. They are heavy and strong, and they don't stretch much, so they work well in shallow water where boats need steady holding power. They are also easy to maintain, long-lasting, and cost-effective. Their weight capacity makes them a better choice for the catenary system of mooring. Chains come in different sizes, grades, and rules, depending on how much fatigue, application, and strength they need. They can be made with or without studs. The studs in the chain give it weight and stability, which helps it stay on the seabed while handling. When the studs are removed, the chain's weight is reduced, which increases its fatigue life. Studless link chains are used for permanent moorings (Gordon et al., 2014).

2.1.2.8 Mooring Winches, Capstans, and Their Operational Mechanisms

Mooring winches and capstans are important parts of ships that pull in and let out the ropes that keep boats in place. Winches today have smart features like automatic tension systems that keep ropes tight without any help from people and remote controls that let workers use them from safe places far away. When the ship moves because of loading cargo, changing tides, or waves, these systems automatically tighten or loosen the ropes. A simple winch has a round drum that holds the rope, a motor (usually electric or hydraulic) that gives it power, and gears that make it strong enough to lift heavy things (Villa-Caro et al., 2014). A strong frame holds everything together and also holds important parts like the brakes and clutches.

These automatic systems make mooring safer and easier, but they also make things harder in new ways. Workers now need more training to learn how to use the machines, not just how to use

them by hand. Many accidents happen because operators don't know how to use the automatic features correctly, can't talk to each other well, or haven't had enough training on the new technology. If crew members don't know how to use these smart systems or how to take manual control in an emergency, the same technology that was meant to keep them safe could cause new kinds of accidents. This means that training programmes need to teach both the old ways of doing things by hand and the new ways that use computers.

2.1.2.9 Bollards, Fairleads, Chocks, and Other Deck Fittings

Deck fittings are the metal parts on ships that hold and guide mooring ropes. They have to deal with the huge forces that happen when boats dock. These include strong cast steel chocks and bollards that are welded straight onto the deck so that boats can be tied up. Fairleads change the direction of ropes, and they often have rollers to make this easier. Depending on their needs, ships also use special tools like chain stoppers, quick-release hooks, and swivel fairleads. The size and placement of these parts are very important. Different types of bollards, such as cleats, bitts and pillars, are better for different jobs and weight loads.

The most stress in the mooring system happens where the ropes connect to the deck fittings (Gordon et al., 2014). Engineers need to carefully plan these connections with the right curves and strengths. For instance, fairleads need to have the right bend radii so that ropes don't lose strength when they bend around them. The industry has a smart rule: ropes should break before the ship's fittings do. This makes sure that weaker parts fail first to protect more expensive equipment. If these connections aren't made right, like using the wrong size ratios, weak bollards, or bad alignment, the ropes will wear out quickly and break, even if they are brand new and of high quality. This is why all the parts of a mooring system need to work together as a whole instead of just picking out individual parts.

2.1.2.10 Fenders

When boats tie up or come alongside, marine fenders are cushions that keep them from damaging the docks or the boats. When a ship hits the dock, it absorbs the energy, which protects both the port structure and the ship. There are many different shapes and sizes of these safety devices. Some are made of foam, some are filled with air, and they work great for ship-to-ship operations. Some are shaped like cells, and some are cones that work well when the tides change.

The type to use depends on a number of things, such as the type of port, the size of the ships, and the weather in the area (Morgan, R. 2021).

On the other hand, fenders only work well if they are made of high-quality materials, are the right size for the job, and are kept in good shape. When docking, fenders that are broken or damaged might make problems worse instead of better. Ship captains need to check the fenders very carefully, especially in places they have never been before, to make sure they are strong enough for their ship. This means figuring out how many tugs are available, how many fenders there are, what shape they are in, and if they are the right size and type for the ship and the weather (Van der Molen, 2015) . Fender systems that break down or don't work right can cause costly damage, long delays, and serious safety issues that affect all of the port's operations.

2.1.3 Forces Acting on Moored Vessels

When ships are docked, they are exposed to a lot of different environmental and water movement forces that put a lot of stress on their mooring ropes and equipment. When boats are docked, they are pushed and pulled by a complicated mix of natural forces, such as waves, wind, and currents.

2.1.3.1 Wind and Current Forces

I. **Wind Forces:** Strong forces are created when wind strikes a ship's exposed areas above the sea, particularly on large ships. We can calculate the strength of this force using a formula that accounts for the air thickness, the squared wind speed, and the area of the ship exposed to the wind. The direction of the wind and the ship's position have a significant impact on the amount of sideways and front-to-back force generated. Wind striking a ship's side, for example, pushes sideways far more forcefully than wind striking the front or rear.

II. **Current Forces:** Ocean currents can exert a lot of stress on ships that are docked. When powerful currents and high winds meet, especially during major storms, the two can tug mooring ropes so near to breaking that they snap. This is especially true when some ropes are stronger than others. Special arithmetic formulas that use the speed of the current, the thickness of the water, and the underwater part of the ship can help figure out the sideways and longitudinal current forces.

III. **Interaction with Passing Vessels:** A major force comes from other ships passing by. When a vessel moves through the waterway past a docked ship, it can create changing forces that push and pull the moored vessel lengthwise, sideways, and in rotating motions. How strong these forces are depends on several things: how much water space is under the ships (less space means stronger forces), how big both ships are, which direction the dock faces, and, most importantly, how fast the passing ship is going, since the force grows with the square of its speed.

2.1.3.2 Hydrodynamic Effects

I. **Squat Effect:** The squat effect arises when ships go through shallow water. This is a problem with how the water moves. It lowers the pressure under the ship's bottom, which makes the ship sit deeper in the water and makes the distance between the ship and the sea floor smaller (Wanhai, X et al., 2025). According to the rules of fundamental water flow, this happens because the narrow space between the ship's hull and the bottom makes the water move faster, which lowers the pressure. As the ship flies faster, the squat becomes stronger. The squat effect can make ships run aground when they shouldn't and make it impossible to steer them.

II. **Interaction with Port Infrastructure:** The water can move in ways that make boats that are docked move back and forth, side to side, and spin around when ships pass by. The strength of these forces changes depending on a number of things, like how much space is under the ship (less space implies stronger forces), the size of the ships that are interacting, and the direction the berth faces (G.F. Remery, 1974). These kinds of abrupt motions can really hurt the ship's boarding ladder or walkway, mooring ropes, fenders, and even the dock itself. In the worst circumstances, these interactions might rupture cargo pipes, which can be bad for the environment. To stop these undesirable movements, it's vital to always replace the ropes when the tide changes or when cargo work is going on and to keep the appropriate mooring configurations.

2.2 Mooring System Failure Modes and Mechanisms

This part sorts out and talks about the different ways that mooring systems can fail, as well as the reasons why they do, for a better understanding of the flaws that are built into these important maritime activities.

2.2.1 Classification of Mooring System Failures

Mooring system breakdowns can be divided into three main groups: equipment breakdowns, operational breakdowns, and environmental breakdowns. These breakdowns can show up in different levels, from small performance problems to complete loss of the ship's ability to stay in position, with potentially wide-reaching and serious results.

I. **Equipment Failures:** These things happen when any portion of the mooring system's physical pieces breaks, stops performing properly, or becomes spoilt in any way. Mooring ropes breaking or cracking, winches or windlasses not working, bollards toppling over, or other vital deck equipment like chocks and capstans not working are all regular difficulties. Things like these happen a lot because materials get poorer over time (such as wear, weariness, or rust), the design wasn't good enough to begin with, or something went wrong during production. One such case was when a bollard fell down because the bolts that kept it in place were too rusted. This indicates that equipment can break down if it is not designed or maintained properly.

II. **Operational Failures:** These problems happen when people make mistakes, don't do things in the appropriate order, or have issues with management and supervision. Some examples are not properly tightening mooring ropes, not handling ropes correctly on winch drums or strong points, poor communication among the mooring team, not training workers, or not following general work regulations (Hsu, 2014). The need to do tasks fast and a lack of a culture of safety make these problems worse. They cause accidents or damage that make things less safe.

III. **Environmental Failures:** These happen when the mooring system is put under too much stress by outside forces, which can cause it to lose control or break down. This group includes events that happen when the weather is very bad, like very strong winds, strong

currents, or rough waves, which make it impossible for the system to keep the boat in place. The marine environment can also cause long-term damage to materials, which can make equipment fail faster in normal or mild weather.

2.2.2 Root Causes of Mooring Failures

You need to know what causes mooring failures on a basic level in order to make good plans for stopping them and fixing them. These causes are often stacked on top of each other and work together. Causes of mooring failures are as follows:

A, Material Breakdown

Mooring ropes and related parts are constantly exposed to the harsh ocean environment, causing different types of material breakdown.

I. **Wear and Abrasion:** This happens when parts of the mooring rope rub against each other, the ship's structure, or the bottom of the sea. This rubbing makes the rope thinner and weaker, which could make drag and tension worse.
II. **Fatigue:** Mooring parts are constantly being stretched and bent because of changing loads. Over time, this repeated loading can cause tiny cracks to form and spread, which can lead to sudden and often disastrous breaks without warning. The real load cycles and weather can cause a lot more fatigue damage than was first thought during the design phase (Junfeng D., et.al, 2020). Out-of-plane bending, especially at fairleads and chain stoppers, is k nown to make fatigue failure happen much faster.
III. **Corrosion:** This chemical reaction between the mooring material (especially steel parts) and the saltwater around it is a common problem. Rust happens faster in oceans with a lot of salt and chloride ions. Rust pits and defects are places where stress builds up and cracks start, which seriously damage the material's mechanical and fatigue properties. Tribocorrosion, which is when mechanical wear and rust happen at the same time, is a big problem for the maritime industry. (Conghao D. et.al., 2020)
IV. **UV Breakdown:** Synthetic fibre mooring ropes can break down from ultraviolet (UV) radiation, which can weaken their material properties due to long exposure.

V. **Sea Life Growth:** Algae and barnacles are examples of sea creatures that can build up on mooring ropes, especially fibre ropes. Such growth can make the ropes rust faster and make them heavier and increase the rope's drag. This extra weight and drag can change the rope's natural frequency and make it wear out faster.

B. Design Problems and Manufacturing Defects

Basic issues in the design and manufacturing processes of mooring systems can create hidden weaknesses in them, making them more likely to fail when in operation.

I. **Design Problems:** Sometimes, new types of failures that weren't properly predicted or planned for in the original design can cause mooring failures. Examples include out-of-plane bending, chain hockling (twisting), poor flash welds, and parts with naturally low metal toughness. These design-related weak points get worse because mooring systems are getting bigger and better; it's difficult to predict how loads will change, and capacity influences aren't being modelled properly.

II. **Manufacturing Defects:** Small cracks, pits, or internal breaks that happen during the manufacturing process can lead to bigger problems later on in the equipment's life. Using dirty materials, improperly heating them, ignoring assembly instructions, or failing to coat and lubricate them adequately can all cause these problems. These defects are scary because they may not be found during the first quality control check, but they are likely to happen and can be costly to fix later.

C. Poor Maintenance and Inspection Systems

Problems in maintenance and inspection practices directly contribute to a large number of mooring failures.

I. No Forward-Thinking Management: Mooring systems are well-made, but people often forget about them after installation. This reactive approach, instead of management that looks ahead, is a big reason why things like lost anchors and chains happen.

II. Insufficient Procedures: A complete Mooring Integrity Management (MIM) Plan is a very important part that is missing or not being used well. A good MIM plan should have regular inspections, computer modelling to find high-risk parts, estimates of how long parts will last based on their current condition and breakdown rates, and clear repair procedures.

III. Poor Monitoring: Poor inspection systems often don't find loose parts or keep an eye on the condition of important safety measures like cathodic protection anodes. For jacketed synthetic mooring ropes, looking at the outside jacket isn't a good way to tell how the internal load-bearing fibre is doing; you need more advanced inspection methods.

IV. Challenges in Following Rules: The IMO's international guidelines (MSC.1/Circ.1620) say that inspections and maintenance should be done on a regular basis based on the manufacturer's suggestions and the operator's experience. However, it is still a big problem in the industry to consistently and thoroughly follow these rules.

D. Human Factors

Human factors are mostly mentioned as the main cause of mooring failures and other maritime accidents. The European Maritime Safety Agency (EMSA) reported that 58.4% of maritime accidents are related to human actions.

I. **Work Mistakes:** These include mistakes made directly while mooring, like tying ropes too tightly, not using winches correctly, and basic communication problems among the mooring team.

II. **Lack of Training and Skills:** Accidents happen a lot because workers don't know how to deal with changing loads on mooring ropes or how modern rope materials work (which may be very different from traditional ropes). Not enough training can make it hard to use equipment correctly or respond quickly in an emergency.

III. **Lack of Awareness:** Not knowing about snap-back zones and how to safely position yourself while mooring is a major problem that can cause serious injuries and even death. Crew members are often put in dangerous places, even though there is a lot of documentation and warnings.

E. Environmental Factors

Beyond just putting forces on systems, the ocean environment can actively break down and damage mooring systems.

I. **Harsh Ocean Environment:** The high salt content of seawater and the presence of elements that cause rust make metal mooring parts rust faster. Tribocorrosive effects, which happen when mechanical wear and rust happen at the same time, make this breakdown even worse.

II. **Unpredictable Weather Events:** Sudden and unpredictable changes in the environment, like strong currents and big changes in the tide, put extra stress on mooring equipment that is often unexpected. These conditions can also make workers tired, which makes it more likely that they will make mistakes.

III. **Physical Contact with Sea Bottom:** Because tides and currents constantly move traditional chain moorings, the chains drag along the bottom of the sea. This dragging action wears down the chain links and leaves mooring scars on the seafloor, which hurts fragile ocean ecosystems like seagrass beds and stirs up sediments. The disturbed sediments can let go of nutrients and pollutants that were trapped in them, which can make the water quality worse and hurt marine life.

2.2.3 Consequences of Mooring System Failures

The effects of mooring system failures are very bad and affect safety, the economy, and the environment.

A. Safety Hazards

The most immediate and critical results of mooring system failures are the significant safety dangers posed to workers, often causing severe injuries or deaths.

I. **Snap-back Incidents:** When a mooring rope breaks under tension, the stored energy is released in a violent way, causing the ends of the rope to snap back or recoil at very high speeds (possibly over 500 km/h). Anyone who is in the snap-back zone is at risk of serious injury or death, such as losing limbs, being decapitated, getting a traumatic brain

injury, damaging their spine, getting severe cuts, or dying. Synthetic tails can make things more stretchy, but they can also store more energy and make snap-back more likely.

II. **Rope Bight Accidents:** Crew members who get caught in the bight (the inside of a coil) of a moving mooring rope can get tangled up, thrown into machinery, or pulled overboard, which can cause serious injuries or death.

III. **Equipment Breakdown and Crashes:** Injuries can happen if winches or other equipment don't work properly. If a ship's mooring fails, it can move around uncontrollably, which can cause it to crash into other ships or port structures. This puts both shipboard and shore-based workers at risk.

IV. **High Rate of Injuries:** Mooring operations are always seen as high-risk, and they are one of the most common causes of personal injury in the maritime industry. Reports show that a large number of serious injuries and deaths happen while mooring or towing, and most of these injuries are caused by ropes and wires.

B. Economic Impacts

Failures in mooring systems have big effects on the economy, hurting ships, port structures, and the overall efficiency of the supply chain.

I. **Vessel and Berth Damage:** If a vessel's mooring fails, it can move around uncontrollably and crash into the berth, other vessels, or port facilities. This can cause a lot of structural damage to the vessel's hull, accommodation ladders, walkways, and the berth itself. This damage needs expensive repairs and could cause the operation to be down for a long time.

II. **Operational Delays and Downtime:** When mooring fails, it directly affects port operations, causing ships and trucks to wait longer and making logistics much more difficult. Berth downtime, which is the time a ship can't load or unload cargo, is an important factor in a port's ability to make money. If things get dangerous, ships may have to disconnect and anchor in open water, which will cost more for tugs and cause more delays.

III. **Increased Operational Costs:** Port congestion and delays make it more expensive to hire workers because dockworkers have to work longer hours and overtime. They also make it harder to divide up resources, which lowers the overall productivity of the port. Inefficiencies in handling cargo, ongoing shortages of imported materials, multiple taxes, and inefficient transport systems all add to the costs of running a business.

IV. **Cargo Loss and Supply Chain Disruptions:** If a ship moves around without control, it can damage cargo hoses or bunker lines, which can lead to cargo loss and pollution of the environment. Port congestion causes congestion that affects the whole supply chain, making it harder to manage inventory and causing a lot of inefficiencies.

V. **Reduced Revenue and Competitiveness:** For ports, problems with mooring and the delays that come with them directly cut into the money they could make from customs and tariffs. For countries, port inefficiencies that last a long time make them less competitive in global trade and slow down economic growth. In West Africa, Nigerian ports have some of the highest cargo clearing costs, which leads to long wait times and lower income.

C. Environmental Damage

When mooring systems fail, they can cause a lot of damage to the environment, especially through oil spills and damage to marine ecosystems.

I. **Oil Spills and Pollution:** Tankers and other ships that carry dangerous cargo and don't have a way to steer can crash or run aground. This can hurt the hulls or cargo tanks and cause oil spills or the release of dangerous materials. These kinds of spills are bad for marine plants and animals. They hurt ecosystems in the water and on land, make beaches dirty, and make fish unsafe to eat. Chemicals that come from oil are usually bad for you, can cause cancer, or can build up in the food chain in the ocean. Spills from tanker accidents or very big drilling activities can have effects that last for decades.

II. **Habitat Destruction:** Traditional chain moorings cause a lot of physical disturbance because they are always dragging on the bottom of the sea due to tides and currents. This action destroys fragile marine ecosystems like seagrass beds (which are important places for marine life to grow) and lowers biodiversity.

III. **Water Quality Problems:** Chains that drag along the bottom of the water also stir up sediments, which makes the water cloudier. This makes it harder for light to get through and makes it harder for marine plants to photosynthesise. When sediments are disturbed, they can let go of nutrients and pollutants that were trapped inside them. This can lead to algal blooms and make the water even worse.

IV. **Impact on Marine Species:** Marine species are directly affected by the destruction of habitats and changes in water quality. This causes fish populations to drop and makes it harder for larger marine animals like whales and dolphins to move around. Sensitive species can also be bothered by the noise and vibrations of chains being dragged. A wide range of aquatic vertebrates can be hurt, cut, or killed directly by vessel crashes.

2.3 Mooring System Operations and Challenges in Nigerian Seaports

This section focuses on the specific operational environment and unique challenges faced by commercial vessels and port operators in Nigeria, particularly concerning mooring systems.

2.3.1 Overview of Nigerian Seaports

Nigeria's seaports are important for trade and business in West Africa because they can handle many different types of commercial ships. The Nigerian Ports Authority (NPA) runs and controls the main port complexes, such as the Lagos Port Complex (Apapa), the Tin Can Island Port Complex, the Calabar Port Complex, the Delta Ports (Warri), the Rivers Port Complex, the Onne Port Complex, and the newer Lekki Deep Sea Port.

These ports can handle different kinds of commercial ships:

I. **Cargo Ships:** Big ports like APM Terminals Apapa and Lekki Deep Sea Port can handle big cargo ships, even the ones that run on LNG and are getting better all the time. This shows that shipping is becoming more eco-friendly.

II. **Bulk Carriers:** Ports like Tin Can Island can handle dry bulk cargo since they have big grain silos and other equipment.

III. **Tankers:** Many oil tankers come and go from Nigerian ports, especially those in the Niger Delta region (Onne, Warri, Bonny, Escravos, etc.), to bring in and take out crude oil and other petroleum products.

IV. **Roll-on/Roll-off (RORO):** Tin Can Island Port, for instance, handles RORO cargo.

V. **General Cargo Vessels:** Many ports deal with different kinds of breakbulk and general cargo.

2.3.2 Infrastructural and Operational Challenges

Mooring operations in Nigerian seaports are significantly impacted by a range of persistent structural and operational challenges.

I. **Port Congestion:** Port congestion is a regular problem that makes trucks and ships wait longer. This makes logistical networks work much more slowly. For example, various ports throughout the world have dwell durations of three to nine days. But Nigerian ports generally take weeks to clear goods, which is a lot longer than the 12 to 24 hours that ports that work better usually have to wait. This traffic backlog makes it impossible for the port to run properly, which causes problems like having to pay more for workers who work extra hours and having trouble with resource allocation.

II. **Inadequate Berth Infrastructure:** A lot of Nigeria's ports have ancient and poorly maintained berths, quays, and bumper systems. Ships get damaged a lot and are late to dock since they don't have adequate resources. If the bumpers are made of cheap or low-quality material, for instance, they might hurt both ships and berths when they hit each other. The design and strength of the bollards are also highly critical for mooring to work. They can change how things work if they aren't strong enough. Even though much money has been spent on it, the wait times and challenges with berthing haven't gotten significantly better.

III. **Outdated Equipment and Inadequate Cargo Handling Systems:** Many ports have obsolete equipment and not enough ways to transport containers, which makes shipping more expensive and takes longer. This also makes docking operations less efficient because the whole port is less organised.

IV. **Navigational Constraints:** Some ports, like Calabar Seaport, are hard to get to because the rivers are too shallow for larger ships to go through. This means that the rivers need to be dug out a lot. This can make it tougher for some ships of different types and sizes to dock at the port, which can modify how ships are tied up.

V. **Poor Interconnected Roads:** The highways that run to significant ports like Warri, Onne, and Calabar are in horrible shape, and there aren't enough train links to regions where things are created. This makes moving goods less efficient, lengthier, and more expensive.

VI. **Regulatory and Governance Issues:** Some of the things that slow down the system and make it less efficient are high port fees, long queues at customs, too many taxes, bad planning, limited coordination among stakeholders, and rampant corruption. These things make Nigeria less competitive and less likely to entice people to invest.

2.4 Regulatory Frameworks and Industry Best Practices

This section talks about the rules, standards, and guidelines that govern the design, use, and upkeep of mooring systems on both a national and international level. It also talks about how these rules help keep the seas safe.

2.4.1 International Maritime Organisation (IMO) Guidelines

International Maritime Organisation (IMO) Standards

The International Maritime Organisation (IMO) plays a central role in establishing global standards for maritime safety, including complete guidelines for mooring systems.

I. **MSC.1/Circ.1619 (Guidelines on the design of mooring arrangements and the selection of appropriate mooring equipment and fittings for safe mooring operations):** This circular, which goes into effect on December 11, 2020, gives detailed advice on how to design mooring arrangements and choose the right equipment. It talks about important things like the Ship Design Minimum Breaking Load (SDMBL), the Line Design Break Force (LDBF), and the Tail Design Break Force (TDBF), and it tells you how they are related and what safety margins you need. The guidelines also talk about how to choose mooring winches (suggesting that the brake capacity be less than or adjustable to SDMBL to avoid overload) and how to set up mooring ropes, capstans, and winches so that there are clear views, the risk of snap-back is low, and direct leads are encouraged.

II. **MSC.1/Circ.1620 (Guidelines for inspection and maintenance of mooring equipment, including lines):** These guidelines, which were passed in November 2020, inform you

how to check and take care of your mooring ropes and equipment while they are in operation. They created rules on how to find old ropes that need to be taken down and how to choose new ones to use. Some of the greatest things you can do are to have clear regulations for mooring, inspect the ropes often as the manufacturer recommends and as you have learnt from your own experience, and replace them before they show symptoms of wear or damage. The circular also talks about how crucial it is to keep proper records of mooring ropes, tails, and other attachments. It also speaks about how to prevent wire ropes from rusting and how vital it is to think about factors like the bend radius (D/d ratio).

III. **Other Relevant IMO Circulars and Conventions (e.g., SOLAS):** Changes to SOLAS Regulation II-1/3-8 will take effect on January 1, 2024. When these rules go into effect, they will set new safety criteria for all ships when they are docked. These guidelines, together with Circulars 1175/Rev.1, 1619, and 1620, highlight how crucial it is to examine and maintain mooring equipment regularly to make things safer and lower hazards. Shipowners and management must now incorporate in their Safety Management Systems (SMS) plans for maintenance and inspections on board. The initial or first safety construction surveys must check these methods. This covers methods for identifying and using mooring ropes, checking them regularly, and making sure that the manufacturer's instructions for changing ropes are easy to find and follow.

2.4.2 Classification Society Rules and Standards

Maritime classification organisations play a crucial role in the shipping industry by setting and enforcing technical standards for the design, construction, and operation of ships and offshore facilities. Lloyd's Register (LR), DNV (Det Norske Veritas), and ABS (American Bureau of Shipping) are some of the most important classification organisations. They make detailed rules and standards that ships must follow in order to get certified.

I. **Lloyd's Register (LR):** LR's guidelines and standards set the right standards for designing, building, and maintaining ships, offshore structures, and shore-based facilities for the whole time they are in use. Through ongoing research and development, these standards are updated on a regular basis to keep up with changes in technology, the

industry, and the law. Regulatory compliance systems usually make these rules available.

II. **DNV: DNV,** a leading classification organisation, offers optional class designations, like "Mooring" (DNV-RU-SHIP Pt 6 Ch 5 Sec. 25), to make sure that new vessels after January 1, 2024, follow SOLAS II-1/3-8 and related IMO guidelines (MSC.1/Circ.1619 and MSC.1/Circ.1620). DNV offers consulting services to ships that are already in operation. These services include help with inspection and maintenance programmes, mooring line management programmes, ship design minimum breaking load (MBLSD) calculation, mooring risk assessment, and location-specific mooring evaluation.

III. **ABS (American Bureau of Shipping):** Like DNV, ABS is a private group that works to improve public health and meet client needs by making and verifying standards for the design, construction, and operation of marine-related facilities.

2.4.3 Industry Best Practices

In addition to rules that must be followed, industry best practices give a lot of guidance on how to make mooring systems safer and more effective. They also often predict what new rules will be needed. The Oil Companies International Marine Forum (OCIMF) Mooring Equipment Guidelines (MEG4) are a great example.

2.4.3.1 OCIMF Mooring Equipment Guidelines (MEG4): The fourth version of MEG4, which came out in 2018, sets minimum standards for making mooring systems safer, more effective, and better designed. It comes from the work of shipping industry groups, mooring rope makers, equipment providers, and shipbuilding facilities working together.

Main concepts and improvements brought by MEG4 include:

I. **Uniform Language:** MEG4 clears up language and makes it consistent by replacing vague terms like Minimum Breaking Load (MBL) with clear ones like Ship Design Minimum Breaking Load (SDMBL), Line Design Break Force (LDBF), and Working Load Limit (WLL) to stop users and makers from getting confused.

II. **Improved Direction:** Gives new rules for buying, keeping an eye on the condition of, and retiring mooring ropes and tails. It stresses that ropes must have at least 75% of the SDMBL's average remaining strength before they can be retired.

III. **Human Element Inclusion:** Adds new sections that focus on important safety aspects of mooring, such as the human factors in mooring design, dock design and equipment, ship-to-shore connection, and new technologies. This is an example of a people-centred design method that lowers risks during operations.

IV. **Management Programs:** If ships can't fully follow MEG4 suggestions, they need to make a Mooring System Management Program (MSMP) and a Line Management Program (LMP). These programmes tell you how to inspect, maintain, and replace things, and they keep a record of everything that happens on the ship while it is in service.

V. **Brake Release Setting:** According to MEG4, the brake release setting for mooring winches should always be set to 60% of the SDMBL. This setting is the main safety feature for the mooring system. It makes sure that the brake releases at a point below other failure loads but above the rope's WLL (Working Load Limit), which means that the winch brake is a controlled weak point.

VI. **Work Factors:** Gives direction on resisting standard environmental conditions (wind, current, tidal forces) and handling additional loads from surge, waves, or ice. It stresses careful mooring rope management to deal with forces from changes in ship height due to tides or cargo work.

2.4.4 National Regulatory Landscape: Nigerian Maritime Administration and Safety Agency (NIMASA) and Nigerian Ports Authority (NPA)

Nigeria's shipping industry works under a set of domestic laws and organisations that were set up to follow international agreements and promote safety, security, and trade.

A. Nigerian Maritime Administration and Safety Agency (NIMASA):

NIMASA is Nigeria's top maritime regulatory and development organisation. It was formed in 2006 by combining the National Maritime Authority and the Joint Maritime Labour Industrial Council. Its powers and responsibilities come mostly from important legal documents:

B. NIMASA Act 2007: This law names NIMASA as the "Maritime Administration" with duties to support, control, and manage public policies in the industry.

C. Merchant Shipping Act 2007: Controls commercial shipping activities, including ship licensing and safety standards.

D. Coastal and Inland Shipping (Cabotage) Act 2003: Works to promote local involvement in maritime activities by limiting foreign ships in coastal commerce, though its success has been questioned by regular exemptions.

NIMASA's main jobs are to keep sailors safe, set standards for sailors, control shipping, support commercial shipping and cabotage activities, and stop and control pollution in the marine environment. The organisation surveys and certifies boats, investigates marine accidents, and makes sure that all of its areas of work follow the rules and agreements that are in place by doing daily checks. NIMASA also follows through on domestic IMO and ILO agreements. It has also started programmes like the Deep Blue Program to make Nigerian waters and the Gulf of Guinea safer for shipping.

2.4.4.5 Nigerian Ports Authority (NPA):

The NPA is the legal entity that runs, develops, and manages Nigeria's ports and harbours. Its principal job is to keep waterways safe and easy to use, as well as to keep all port activities safe and secure. The NPA is the landlord port authority, and it makes sure that the buildings at the port are safe. The NPA normally hires private organisations to run terminal operations.

I. **Main Duties**: The NPA designs and builds operational structures that meet international standards. It also handles leasing and agreement activities, establishes price benchmarks, and makes and enforces laws to help port activities work more smoothly.

II. **Sea and Harbour Services:** The NPA offers critical services such as water surveys to make sure ships can safely navigate, towing and mooring aid for ships, and fuel operations. It also works hard to lower the chances of pollution and handle accidents at sea.

III. **Main Ports:** The Lagos Port Complex (Apapa), the Tin Can Island Port Complex, the Calabar Port Complex, the Delta Ports (Warri), the Rivers Port Complex, the Onne Port Complex, and the Lekki Deep Sea Port are all administered by the NPA.

2.5 Introduction to Maritime Risk Assessment

Checking for shipping risks is an important part of making sure that sea operations are safe and work well. It means looking for, studying, and controlling possible threats to ship safety, worker health, nature protection, or business operations. People who work in shipping face a lot of risks, including problems at work, natural disasters (like oil spills and bad storms), breaking the law, and losing a lot of money because of damaged goods or court fines. Planning to check for risks is the key to sea safety. It helps find and stop threats before they become big problems. It also makes sure that ships follow the rules set by the International Safety Management (ISM) Code, SOLAS, MARPOL, and ISO agreements. (Parmen & Abdullah, 2022).

Most of the time, the work starts by looking for possible dangers. These can be machine-related (like a motor breaking down), nature-related (like storm waves), or people-related (like being tired or poor communication). Once these dangers have been found, they are looked at in terms of how likely they are to happen and how bad the results could be (Vidmar, Peter., et al. 2020). A danger chart is often used to group risks into small, medium, and large. The last step is to put in place measures to stop and control problems. These could be machine controls (like alarms), changes to the rules (like practising for emergencies), or safety gear (PPE). A strong Safety Management System (SMS) is an important part of good risk control. It should include a safety and nature policy, clear steps, set communication lines and rules for reporting accidents and dealing with emergencies. To keep following the rules and always get better at safety plans, you need to check in on them regularly and give feedback.

Checking for shipping risks is a basic part of making sure safety and good work happen. Instead of just reacting to problems, we plan how to find, measure, and reduce dangers. This structured

process, which is based on world codes like the ISM Code, makes sure that groups find possible threats before they turn into big problems (Öztürk & Orkun Burak. 2024). By carefully thinking about how likely and how bad things could be, people can make smart decisions about how to use their resources to deal with the most important risks. This saves money and protects people and the environment. This way of planning, which is made stronger by constant watching and regular checks, is not just following the rules; it's a basic work need that makes everyone stronger when things go wrong and creates a culture of safety in all shipping activities.

2.5.1 Qualitative Risk Assessment Techniques

Ways to check risks without numbers are widely used in shipping work because they can systematically find and judge dangers without needing lots of numerical data.

2.5.1.1 Hazard Identification (HAZID)

Hazard Identification (HAZID) is a systematic and structured approach for a group to discuss potential hazards to projects and work processes, such as shipping conditions, without the use of numerical data. It usually means that a group of individuals with diverse expertise works together to find all the probable sources of hazard in different sections of a project, like planning, building, setting up, running, and finishing. It also implies that they advise adjustments to work that has already been done.

The major goals of a HAZID study are:

I. Find the most dangerous objects and places.
II. Think about what might happen because of these dangers.
III. Find out how well the safety measures that are already in place operate and what is being done to keep people safe.
IV. Find solutions to get rid of, stop, control, or lower the hazards you see.
V. Design and safety management need to get early feedback on safety and risk.
VI. Check back later for official safety investigations to see if the work is clearly to blame for serious incidents.

HAZID looks at several types of hazards, like losing goods, fires and explosions, malfunctioning equipment, people, and natural calamities, using structured prompts and guide words. All of the dangers that were detected, where they came from, what they might do, what precautions are in place today, and how to minimise the risk are all set down in great detail. This makes an output that is in order and may be used to form plans and check on items later. You can use HAZID at any point in a project or process. Even when things are moving quickly or there aren't many resources, this lets you detect dangers early, make quick judgments, and think about risks across time.

HAZID is a simple and flexible solution that helps you detect risks early and in a structured fashion throughout the life of shipping projects, even when they require intricate anchoring work. It's a means for a group to get together and discuss what they know, so that you can get a rough idea of the risks, even if you don't have a lot of information yet. This early discovery is particularly essential because it makes project teams plan with safety in mind. In this manner, companies may choose the safest option and save money by not having to rectify things later. HAZID is the initial step of a more thorough risk assessment, such as HAZOP or QRA. It puts the risks, causes, effects, and safety measures that are already in place in the appropriate order. This makes sure that the biggest hazards get the greatest attention when more study is needed.

2.5.1.1 Failure Mode and Effects Analysis (FMEA)

Failure Mode and Effects Analysis (FMEA) is a systematic, proactive, and rational approach to identifying potential failure modes within a system and its components, along with their underlying causes and consequences. You should look at as many parts, assemblies, and subsystems as you can to learn how they might break and how that would change how the whole system works and stays stable.

The main ideas behind FMEA are:

I. **Finding Failure Ways:** There is a list of all the ways that each part could break.
II. **Study of Failure Effects:** It is known how each failure affects the system's performance and the higher levels.

III. **Root Cause finding:** It looks at the main reasons why things can go wrong, which helps people figure out how to fix them.

IV. **Setting Risk Priorities:** FMEA can use numbers or not, but it usually uses a Risk Priority Number (RPN) model. To get the RPN, you multiply the scores for Severity (how bad the problem is), Occurrence (how likely it is to happen), and Detection (how likely it is that you will find out about the problem before it happens). Failure modes with higher RPNs are improved.

FMEA is used in many different fields, like making medical equipment, shipping, and other things, to make sure that systems are safe and work well. The study helps figure out what the system needs to do to lower the chances of failure, build and test systems to get rid of failures or bring risks down to acceptable levels, and make design choices easier. It also helps you find parts that are important for safety, reliability, and single-point failures.

FMEA is a great way to plan for and deal with risk in systems that make things take longer. It goes into great detail about how each part of the anchoring system could break and what would happen to the whole system if that happened. FMEA is a way to find and rank failures that are related to each other. These plans take into account that expert opinions can be very unpredictable and hard to predict. The goal of FMEA is to stop problems from happening by finding them before they do. This can make it much less likely that problems will happen and the risks that come with them.

FMEA is a structured, powerful, and forward-looking method for finding different types of failures at different levels of a system, checking their effects, and ranking risks based on how serious, how often, and how easy they are to find (using RPN) (ABS, 2020). FMEA helps companies make decisions based on facts that make anchoring jobs safer and more reliable by focusing on prevention and giving them a structured way to think about risks. This is better than just doing anything when things go wrong.

2.5.2 Quantitative Risk Assessment (QRA) Principles

Quantitative Risk Assessment (QRA) is a structured and systematic approach to use numerical data to evaluate the probability of adverse events and their potential consequences. It depicts the

findings as dangers to people, the environment, or commercial property. When compared to other methods that don't employ numbers, QRA delivers a clearer and more objective picture of danger levels.

Some of the most important things that QRA does are:

I. **Measuring Risks with Numbers:** It offers you a number that tells you how risky something is, which makes it easier to compare it to guidelines for how much risk is okay, such as "As Low As Reasonably Practicable" (ALARP).
II. **Helping Decision-Making:** QRA helps people make decisions by showing them which types of incidents enhance the overall risk the most. This enables those who need to make choices to decide where to put their money to decrease the risk.
III. **Showing Acceptable Risks:** To acquire approval to build a big, dangerous plant or make big modifications to operations, you typically have to show that the risks are acceptable.
IV. **Finding Preventive and Reduction Steps:** QRA studies help figure out what sorts of safety obstacles are needed and how effectively they operate.
V. **Checking for Uncertainties:** This step entails making sure that numerical results are strong and accurate by finding the main assumptions and variables that affect risk, especially when the data may have broad confidence intervals.

The QRA procedure usually has a few steps:

I. **Data Gathering:** Getting all the details, like the plants' design, function, location, and weather data, as well as the specifics of the process engineering and the quantity of equipment parts (and how often they break).
II. **Finding Dangers:** QRA employs numbers, but it also uses approaches that don't use numbers for studies like HAZID and FMEA to make sure that all conceivable dangers are taken into account.
III. **Modelling Results:** Using numbers to estimate what might happen, such as release rates, gas dispersion, heat radiation, and explosive overpressure.
IV. **Frequency Study:** A frequency study looks at prior data and part failure rates to figure out how often failures happen in different conditions.

V. **Risk Calculation and Rating:** This includes figuring out an overall risk profile by adding together failure rates and risky locations, rating specific risk levels (like those based on occupancy data), and comparing them to acceptance requirements. Lowering Risk: Figuring out the best and most practicable ways to lower risks to ALARP levels.

2.5.2.1 Event Tree Analysis

Event tree analysis uses decision trees to show the possible outcomes of an initial event that could lead to an end event that is a problem. It also looks at how different systems or barriers can change the outcomes. Event tree analysis helps figure out the different paths or chains of events that lead to different outcomes and does some math on those outcomes. Event tree analysis is often linked to fault tree analysis. The matching fault tree model can tell you how likely it is that the starting event and the complex individual event in the event tree will fail.

Event tree analysis can provide detailed descriptions of potential issues (combinations of events that lead to different types of problems from starting events) and numerical estimates of event frequencies or probabilities. This helps to show how important different failure chains are compared to each other. You can use event tree analysis to look at almost any chain of events, but it works best when there are multiple safeguards or barriers in place to protect against possible outcomes of starting events.

To do event tree analysis, you need to know a lot about the starting event and how it changes over time until it reaches the end events (outcome situations). It is important to know what the safeguards/barriers are meant to do in response to the starting event and what the success/failure standards are for them. To do number analysis, you also need to know how likely it is that all the safeguards and barriers in the event tree will work.

The steps for doing an event tree analysis are:

I. **Setting the limits for the assessment:** Find the physical limits and initial conditions for the system and operational activities that will be studied, and figure out what outcomes are important.

II. **Preparing for the Assessment**: Gather information (like drawings and procedures), pick out starting events that are intriguing, and figure out how to protect against or stop those events from happening.

III. **Performing the assessment:** To do the assessment, you need to create the accident situations for each starting event, make the event tree model to show the accident situations, add individual events to the event tree that may need fault tree analysis, calculate the event tree, look at the results of the accident sequence, and come up with ideas for how to improve things.

IV. **Evaluating assessment results:** Compare the risk results to the acceptance standards, evaluate the contributions to the undesirable outcomes from various situational events, and assess the recommendations for implementation.

2.5.2.2 Fault Tree Analysis

Fault Tree Analysis is a study that looks back in time and shows how logical connections between equipment failures, human errors, and outside events can come together to create a specific danger of interest (Top Event). Fault Tree Analysis takes the causes of the Top Event and uses Boolean logic symbols (like "And" and "Or" gates) to break them down into basic events, which are basic equipment breakdowns, human mistakes, or outside events. Top events are typical events found from other danger identification methods (e.g., HAZID, HAZOP) that need more detailed study. Fault Tree Analysis is beneficial for very complicated systems because it can help you identify the failure path that leads to the top event breaking down.

There are two kinds of studies that Fault Tree Analysis can do:

1. Descriptive accounts of potential issues (combinations of events leading to particular problems of concern)
2. Numerical approximations of failure rates/odds and the comparative significance of various failure sequences and contributing factors.

This method can be used for many things, but it works best for studying system failures that happen when many different things happen at once, like with complicated electronic, control, or communication systems.

To do Fault Tree Analysis, you need to know a lot about the system and its parts, as well as what causes parts to break and how they fail. To do the study, you need detailed drawings and steps. For number analysis, you also need to know how often all the basic events in the fault tree fail. Additionally, considering common cause failures necessitates understanding the dependent failure frequencies of the backup components.

Steps to follow when doing a fault tree analysis:

I. **Setting the limits for the assessment:** Identify the system's and operational activities' physical limits and starting conditions, and describe the unwanted (top) event that will be looked into.

II. **Getting Ready for the Assessment:** Gather information like drawings and procedures, as well as data on failures and chances (if applicable).

III. **Performing the Assessment:** The study process begins by constructing the tree framework and examining each branch with increasing levels of detail, utilising pre-existing numerical data for quantitative analyses. To keep all basic events unique and in line with logical patterns, a solid naming system needs to be implemented. Each basic event must show one separate incident and be broken down in the way that was planned to trigger the gate event. It should only keep the breakdowns that are needed and get rid of the ones that aren't. The logical framework needs to be set up so that the outcomes directly lead to the main event. The study must encompass various breakdown categories, including shared cause breakdowns, human errors, each operational phase, external incidents, and timing requirements for fundamental events. Then, the breakdown tree is used to determine event mixes, main contributors, and related breakdown chances. When it makes sense, maths is used to figure out how often and how likely the main event will happen, which leads to better suggestions.

IV. **Evaluating Assessment Results:** Verify the fault tree results and risk estimates against the standards for acceptance.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Introduction

The quantitative analysis of failures and risk assessments in mooring systems requires a reliable methodological framework grounded in appropriate philosophical principles and a comprehensive design strategy. We want to measure and rank the risks of failures, not just list them. These measures will make it easier to manage risks before they happen. (Sharma and Srivastava 2018)

3.2 Research Philosophy

This research is based on quantitative inquiry, which is usually linked to the positivist tradition. This type of research Researchers use a philosophical-analytical framework to investigate real-world issues. (Dulal 2025). Failure Mode and Effects Analysis (FMEA) is a systematic approach that seeks quantifiable, logical patterns in failure sequences and attempts to utilise existing concepts to anticipate and prevent negative results.

The context of this study, which involves evaluating risk in complex mooring systems, necessitates an advanced epistemological framework. The Risk Priority Number (RPN) derived from the analysis is a quantifiable metric. It relies on expert judgement and the assessment of Severity (S), Occurrence (O), and Detection (D). The reliance on human interpretation and specialised, context-specific knowledge indicates that a strictly positivist approach, which prioritises controlled experimentation and objective measurement, is inadequate.

The study adopts a Post-Positivist perspective. This upholds the integrity of the scientific method by facilitating the development and evaluation of hypotheses, as well as employing statistical analysis to assess outcomes. The Post-Positivist perspective recognises the basic difficulties in identifying pure, objective truth in complex socio-technical systems (Habib 2020). This advances the investigation using precise quantitative methods, isolating and quantifying variables while recognising that the ultimate risk assessment is based on collective interpretations of specialised knowledge.

3.3 Research Design

The study uses a quantitative descriptive and analytical research design. The FMEA guidelines recommend setting up this method in two steps.

The descriptive phase involves systematically identifying and recording possible failure modes, their causes, and their effects on certain mooring system setups. This provides the FMEA with a comprehensive, documented analysis that forms the foundation for the components and procedures under examination. A full system description with block diagrams and stories is needed to set the scope and make sure that everyone who needs to know understands it. The alignment of research design with FMEA requirements is shown in Table 3.1.

In this next step, the descriptive inputs are turned into measurements that can be counted. The process involves the careful aggregation of professional quantitative assessments for the categories of detection (D), occurrence (O), and severity (S) (Peide., et. al., 2023). The last step in the analysis process is to figure out the RPN, which is done by multiplying these three numbers together.

$RPN = S \times O \times D$

The Risk Priority Number (RPN) is used to rank and prioritise risks. The analytical rating helps with proactive risk management by making it possible to objectively tell the difference between important failure modes (ABS 2020).

Table 3.1 Alignment of Research Design with FMEA Requirements

Research Element	Methodological Requirement	FMEA Principle	Academic Rationale
Epistemology	Quantifiable measurement, Hypothesis Testing	RPN Calculation, Risk Ranking	Post-Positivism
Design Scope	Systematic, Documented Investigation	Failure Modes, Causes, Effects	Systematic FMEA Study
Data Collection	Isolating & Measuring Variables	S, O, D Ratings (1-10 scales)	Statistical Analysis

3.4 Population of the Study

This study's population comprises stakeholders in the maritime industry and those actively involved in mooring operations, including marine environmental management officers, shipping operators, regulatory officials, engineers, captains/masters, deck officers, and maritime workers. This precise definition of expertise ensures that the information regarding S, O, and D scores is technically accurate.

3.5 Sampling Techniques

This study utilizes the use of purposeful sampling, sometimes referred to as judgemental or selective sampling, a non-probability sampling technique in which researchers specifically choose participants according to predetermined standards that support the goals of the study (Hassan 2024). Expert sampling is a type of purposive sampling that focuses on selecting individuals with extensive expertise or experience in the topic being studied. This approach is particularly useful when the research requires certain opinions or assessments from experts or from individuals with knowledge and experience in the topic being researched.

3.6 Research Instrument

The data gathering device must satisfy high analytical reliability standards to obtain accurate quantitative data from subjective expert opinions. It ought to be user friendly with Google Forms as well. The instrument must be configured as a survey that incorporates organised interviews, questions, and quantitative results.

For Severity, Occurrence, and Detection, basic FMEA usually uses a simple scale from 1 to 10. However, these parameters signify fundamental theoretical ideas or concepts (e.g., risk attitude, probability of failure). A significant methodological lack is the dependence on single-item questions to assess constructs, which has been shown to be extremely unreliable for deriving academic conclusions.

A structured questionnaire with four parts was used to collect the data, which focused on the following:

I. Mooring equipment and materials
II. Maintenance and inspection

III. Human factors and training
IV. Environmental conditions
V. Risk ratings.

The RPN, which is a multiplication of the S, O, and D (Severity, Occurrence, and Detection), will be calculated using the information obtained from the risk rating.

I. Severity: The Severity (S) Scale was used to figure out the risks There are three areas that the multi-item scale will show what happens when things go wrong: human safety (when people are in danger), property damage (when the ship takes too much damage), and environmental effect. Below is the severity risk rating scale used in the data collection:

Severity (S):

1-2: Minor inconvenience.

3-4: Minor injury or equipment damage.

5-6: Moderate injury, significant equipment damage, or minor environmental harm.

7-8: Severe injury, major equipment loss, or significant environmental harm.

9-10: Catastrophic failure, loss of life, or severe environmental disaster.

II. Occurrence: The Occurrence (O) Scale has ten items that range from 1 (very rare) to 10 (very likely). It uses clear frequency indicators to measure the chance of failure, such as the chance of mooring lines parting under loads. Below is the occurrence risk rating scale used in the data collection:

Occurrence (O):

1-2: Very unlikely to occur.

3-4: Unlikely to occur.

5-6: Moderately likely to occur.

7-8: Likely to occur.

9-10: Almost inevitable.

III. Detection: This scale has several items that measure how well existing control systems (such as alarms, sensors, and inspections) determine the failure mode before any damage occurs. Higher grades, like 10, are more risky because the problem is harder to identify. Below is the detection risk rating scale used in the data collection:

Detection (D):

1-2: Almost certain to be detected.

3-4: Very likely to be detected.

5-6: Moderately likely to be detected.

7-8: Unlikely to be detected.

9-10: Unlikely to be detected.

3.7 Procedures of Data Collection

For this research design, precise data collection was crucial. The research made use of primary data collection only, as it provided firsthand information from people who have practical experience in mooring operations. To gather sufficient relevant information, an organised questionnaire was designed and used. The data collected were mainly quantitative and were presented in numerical and statistical formats to guarantee the reliability and accuracy of the questionnaire's findings. This method was chosen because it aligns with the nature of the research approach, which depends on experience based answers and professional opinions.

The data was collected by an online survey distributed via Google Forms to reach a wide range of respondents. It was distributed to marine engineers, maritime workers, shipyard personnel, and others with experience in the maritime field, yielding a total response of (N=50).

3.8 Procedures Of Data Analysis

Researchers use data analysis methodologies to derive significant insights from the gathered data, which facilitates a simple description of the findings from the collected data. Data analysis is essential in the field of research, as it enables researchers to interpret large volumes of data, identify patterns, and verify hypotheses. In accordance with LeCompte and Schensul, it involves the reduction of data to a narrative that interprets findings and offers insight (LeCompte, and Schensul, 2010). The process is important for the purpose of addressing research questions, influencing decisions, and informing scientific conclusions. The data was analysed with google sheets and visualised with Tableau.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Results

The results derived from the failure analysis and risk assessment of mooring systems involved the distribution of online questionnaires to maritime workers and stakeholders, yielding 50 responses, which were then analysed. This study included a total of 50 selected participants who have experience working with mooring systems and handling mooring operations, and their demographic data are shown in the tables and graphs below as follows:

4.1.1 Socio-Demographics Of Respondents

Table 4.1: Respondents' Role in the Maritime Industry

The table of respondents' data collected on their role in the maritime industry is shown in table 4.1

ROLE	FREQUENCY	PERCENTAGE
Mooring Master	10	20%
Safety Inspector	7	14%
Port Engineer	7	14%
Chief Officer	7	14%
Second Engineer	6	12%
Deck Officer	5	10%
First Engineer	4	8%
Third Engineer	2	4%
Captain/Master	2	4%
TOTAL	50	100%

The graph of respondents' data collected on their role in the maritime industry is shown in figure 4.1

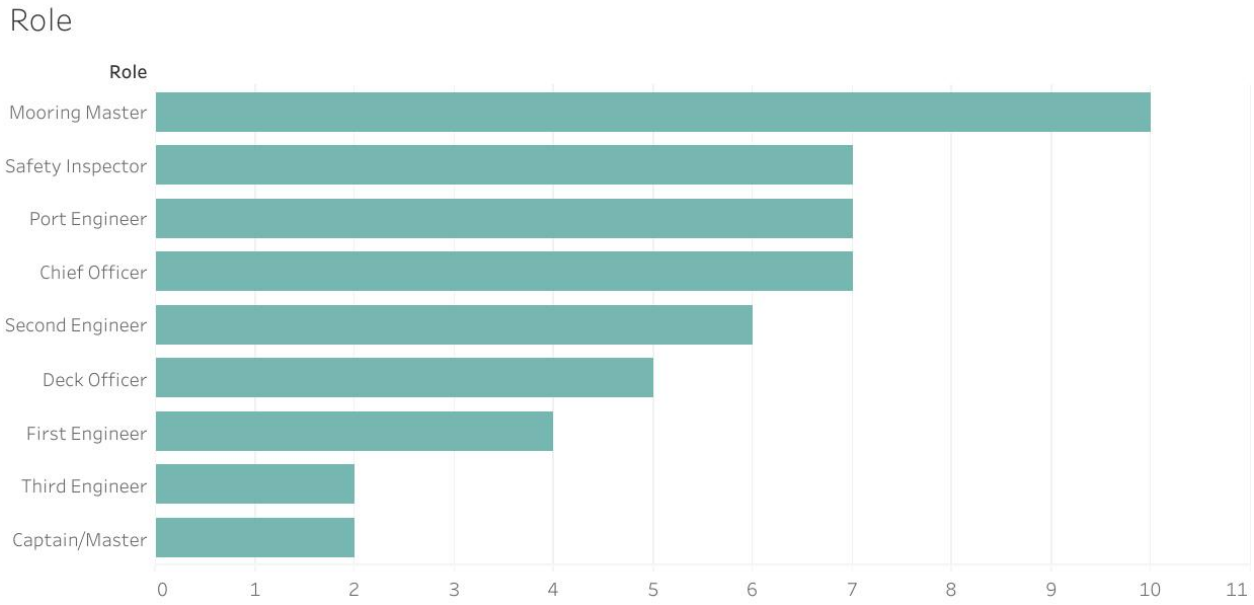

Figure 4.1: Respondents' Role in the Maritime Industry

Table 4.2: Respondents' most common vessel worked with

The table of respondents' data collected on their vessel type is shown in table 4.2

VESSEL TYPE	FREQUENCY	PERCENTAGE
Offshore Support Vessel	10	20%
Cruise Ship	10	20%
Container Ship	10	20%
Tanker (OIl/Chemical)	7	14%
Bulk Carrier	7	14%
LNG/LPG Carrier	5	10%
Anchor Vessel	1	2%
TOTAL	50	100%

The graph of respondents' data collected on their vessel type is shown in figure 4.2

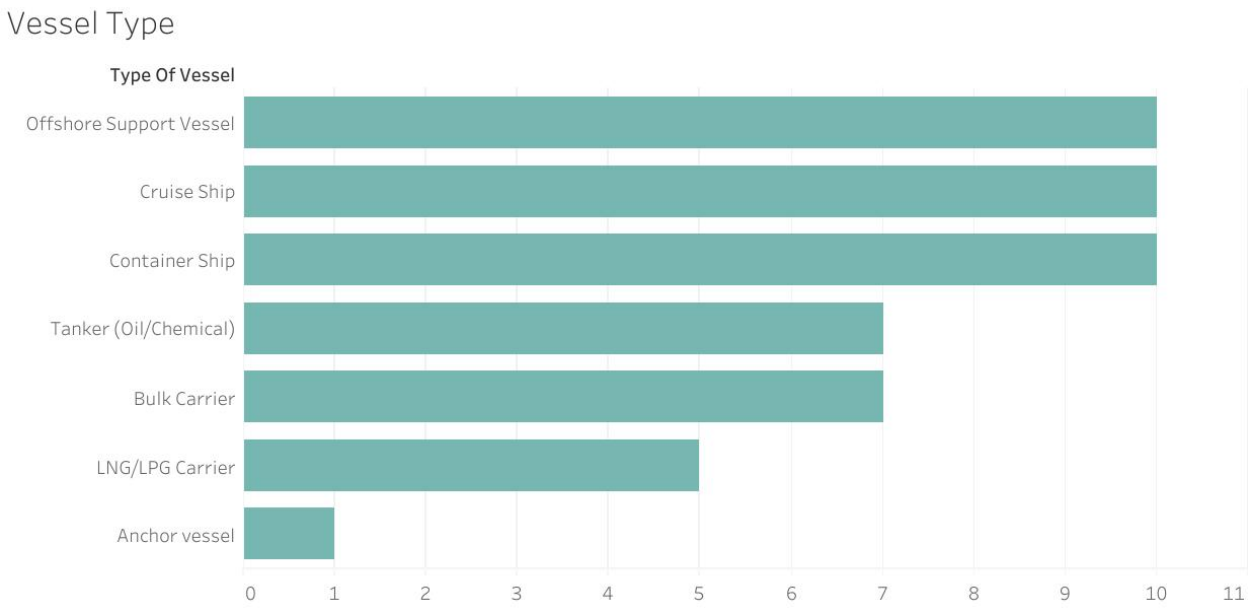

Figure 4.2: Respondents' most common vessel worked with

Table 4.3: Respondents' Years of Experience

The table of respondents' data collected on their age range is shown in table 4.3

AGE RANGE	FREQUENCY	PERCENTAGE
< 5 Years	15	30%
5-10 Years	25	50%
10-20 Years	8	16%
> 20 Years	2	4%
TOTAL	50	100%

The graph of respondents' data collected on their age range is shown in figure 4.3

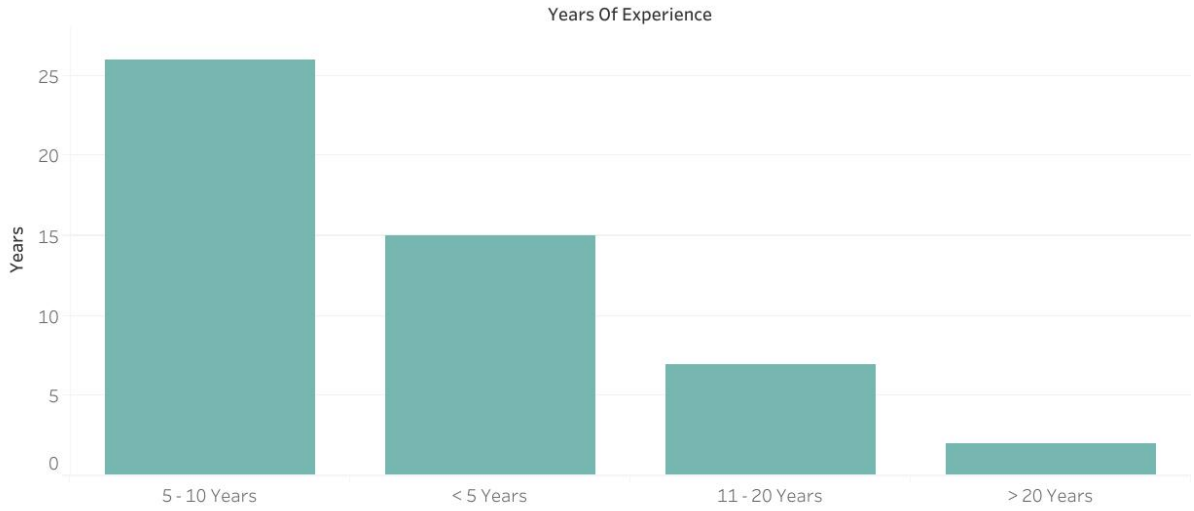

Figure 4.3: Respondents' Years of Experience

4.1.2 Mooring Equipment And Materials

Table 4.4: Most frequent equipment malfunction

The table of respondents' data collected on the most frequent equipment malfunction they experienced is shown in Table 4.4

Malfunction	Frequency	Percentage
Hydraulic Leaks	22	I44%
Winch Brake Slippage	13	26%
Corroded Shackles	10	20%
Fairlead Damage	5	10%
TOTAL	50	100%

The graph of respondents' data collected on the most frequent equipment malfunction they experienced is shown in figure 4.4

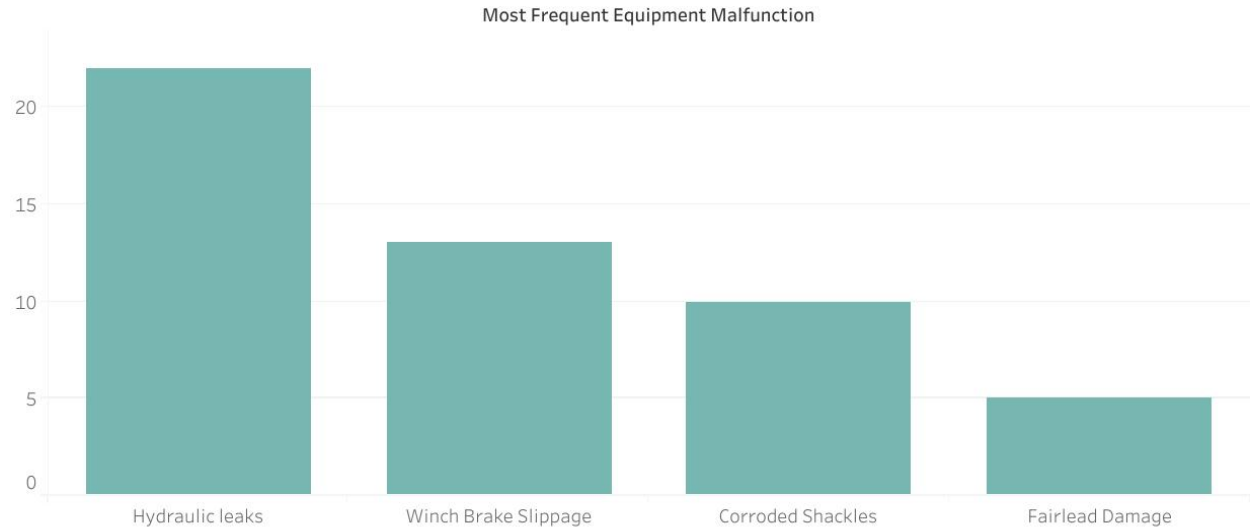

Figure 4.4: Most frequent equipment malfunction

Table 4.5: Common signs of wear observed on Mooring Lines

The table of respondents' data collected on Common signs of wear observed on Mooring Lines is shown in Table 4.5

SIGNS	FREQUENCY	PERCENTAGE
Cuts	16	32%
Powdering Between Strands	13	26%
Fraying	12	24%
Discoloration from UV Exposure	9	18%
TOTAL	50	100%

The graph of respondents' data collected on Common signs of wear observed on Mooring Lines is shown in Figure 4.5

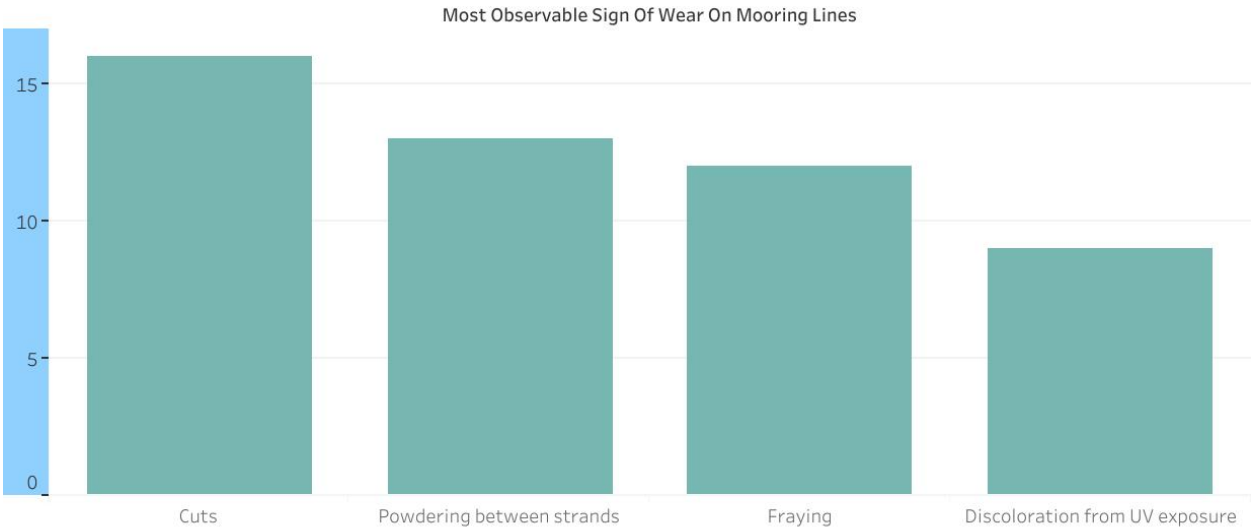

Figure 4.5: Common signs of wear observed on Mooring Lines

Table 4.6: Common cause of Equipment Failure

The table of respondents' data collected on Common cause of equipment failure is shown in Table 4.6

FAILURE	FREQUENCY	PERCENTAGE
Lack of Maintenance	24	48%
Improper Use	13	26%
Environmental Factors	13	26%
TOTAL	50	100%

The graph of respondents' data collected on Common cause of equipment failure is shown in Figure 4.6

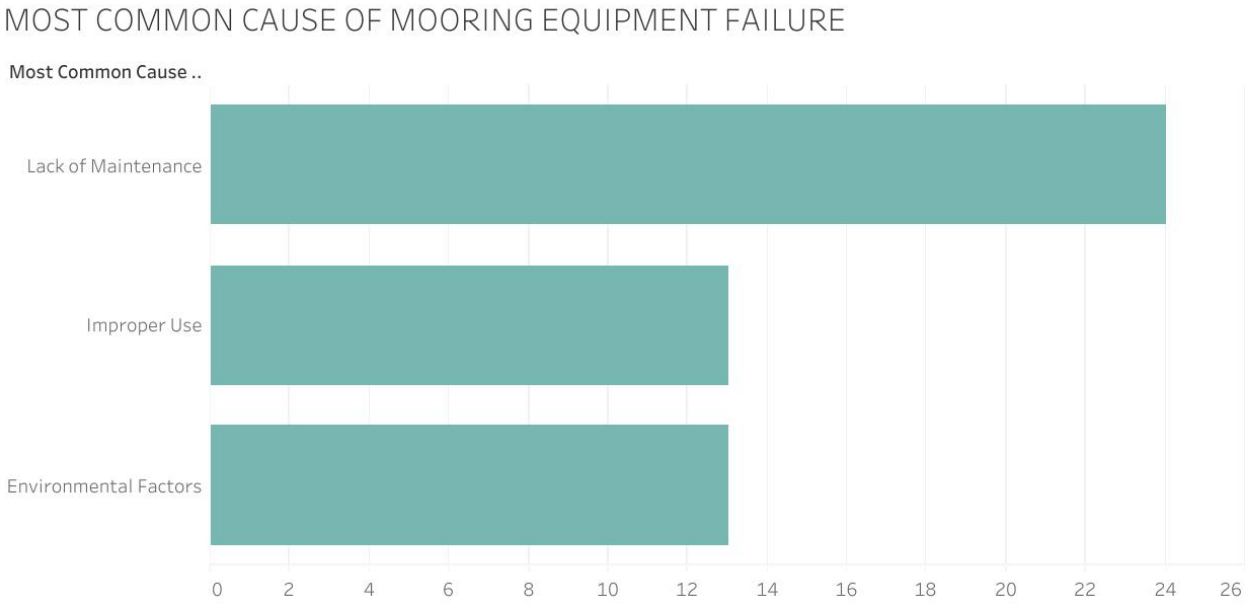

Figure 4.6: Common cause of Equipment Failure

4.1.3 Maintenance And Inspection

Table 4.7: Possession of Formal Mooring System Management Plan (MSMP)

The table of respondents' data collected on Possession of Formal Mooring System Management Plan (MSMP) is shown in Table 4.7

MOORING SYSTEM MANAGEMENT PLAN	FREQUENCY	PERCENTAGE
Yes	38	76%
No	12	24%
TOTAL	50	100%

The graph of respondents' data collected on Possession of Formal Mooring System Management Plan (MSMP) is shown in Figure 4.7

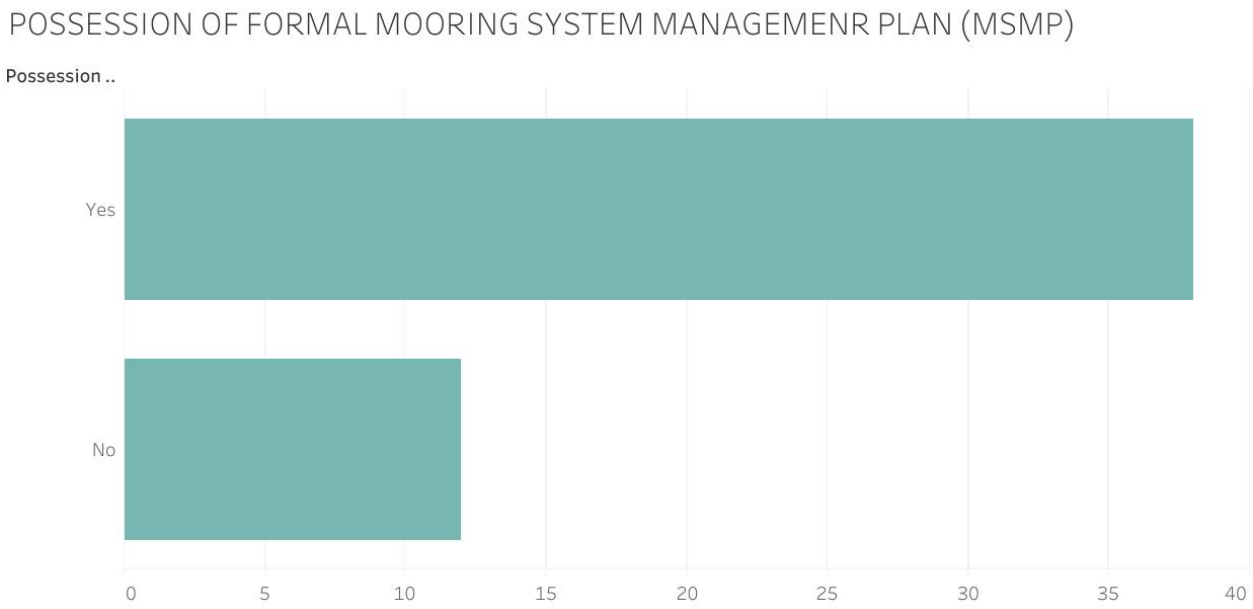

Figure 4.7: Possession of Formal Mooring System Management Plan (MSMP)

4.1.4 Human Factors

Table 4.8: Most Common Human Error leading to Mooring Accidents or Near Misses.

The table of respondents' data collected on Most Common Human Error leading to Mooring Accidents or Near Misses is shown in Table 4.8

ERROR	FREQUENCY	PERCENTAGE
Improper use of Equipment	15	30%
Miscommunication	13	26%
Procedural Violation	10	20%
Incorrect Tensioning	7	14%
Resting on Bollards or Lines	5	10%
TOTAL	50	100%

The graph of respondents' data collected on Most Common Human Error leading to Mooring Accidents or Near Misses is shown in Figure 4.8

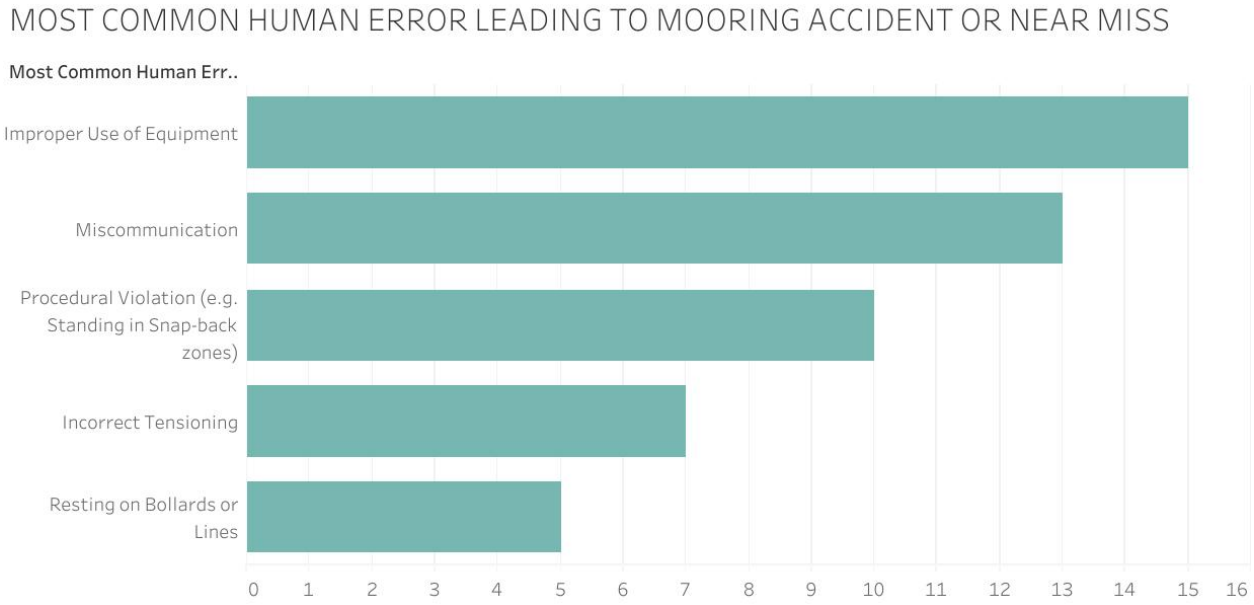

Figure 4.8: Most Common Human Error leading to Mooring Accidents or Near Misses.

Table 4.9: How often Crew Member Deviate from Standard Safety Procedures

The table of respondents' data collected on How often Crew Member Deviate from Standard Safety Procedures is shown in Table 4.9

DEVIATION	FREQUENCY	PERCENTAGE
Rarely	22	44%
Sometimes	21	42%
Never	6	12%
Frequently	1	2%
TOTAL	50	100%

The graph of respondents' data collected on How often Crew Member Deviate from Standard Safety Procedures is shown in Figure 4.9

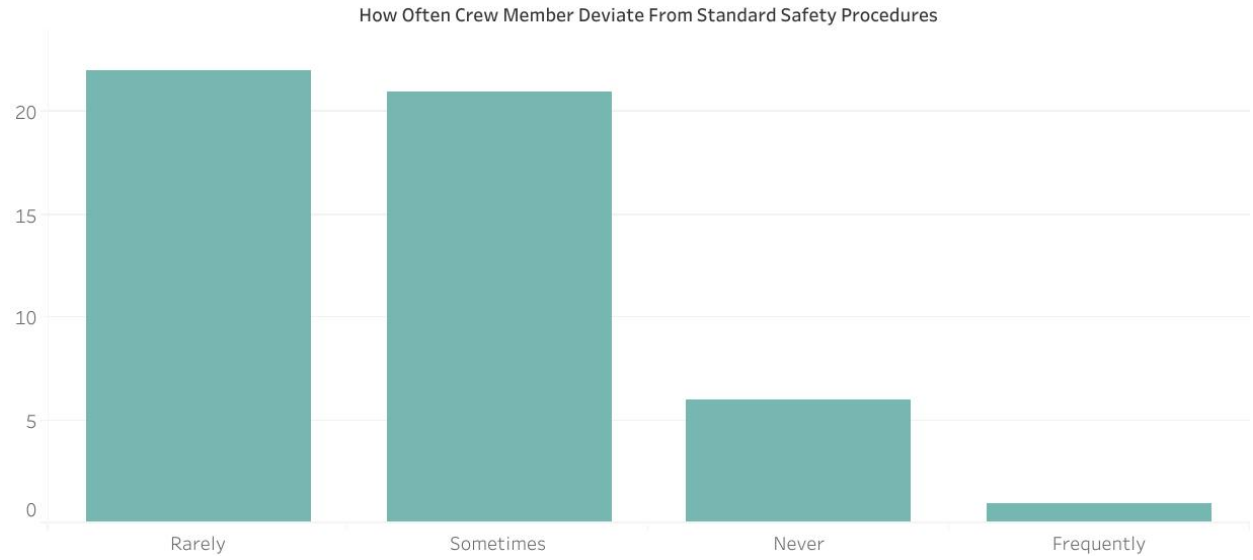

Figure 4.9: How often Crew Member Deviate from Standard Safety Procedures

4.1.5 Environmental Conditions

Table 4.10: Primary Effects Of Adverse Weather Conditions On Mooring Operations

The table of respondents' Primary Effects Of Adverse Weather Conditions On Mooring Operations is shown in Table 4.10

EFFECTS	FREQUENCY	PERCENTAGE
Increased Line Tension	22	44%
Reduced Visibilities	14	28%
Fender Overload or Failure	8	16%
Snapback Hazard	6	12%
TOTAL	50	100%

The graph of respondents' Primary Effects Of Adverse Weather Conditions On Mooring Operations is shown in Figure 4.10

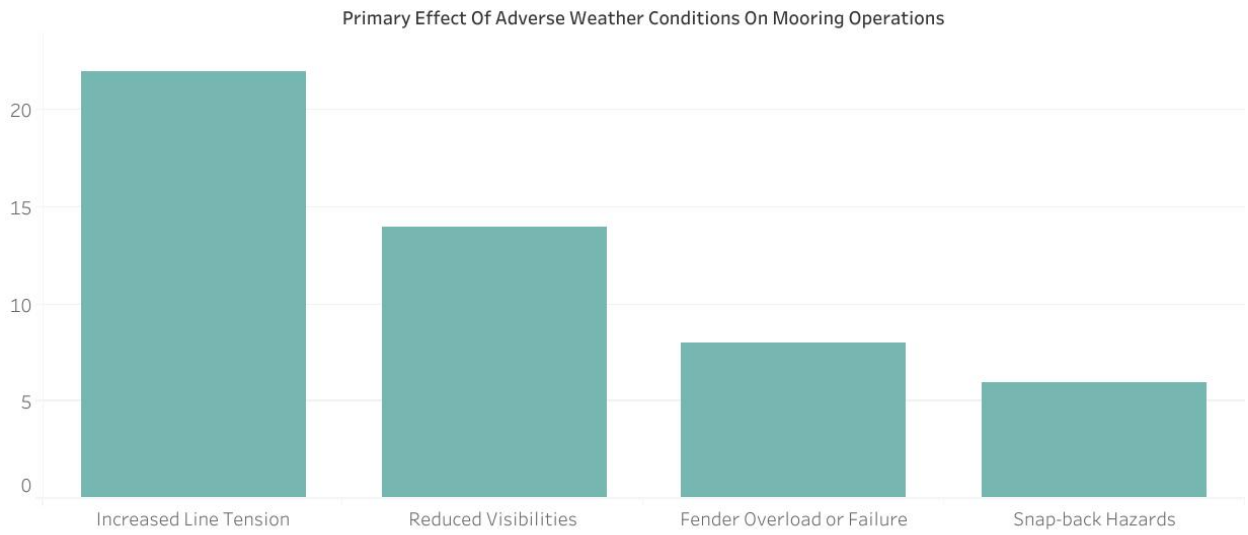

Figure 4.10: Primary Effects Of Adverse Weather Conditions On Mooring Operations

4.2 Failure Mode And Effect Analysis Calculation

A clear and well-defined set of rating scales is necessary for the quantitative application of the FMEA method. These scales, specifically designed for the maritime context, ensure consistent risk evaluation. The next analysis will use the following scales, which are based on industry standards and general FMEA principles.

4.2.1 Fmea Severity Scale (S)

The Severity rating tells you how severe/bad the effect of a failure mode would be on a scale of 1 to 10. A score of 9 or 10 indicates that the situation is extremely dangerous and requires immediate attention.

Table 4.13: FMEA Severity Scale

RATING	CLASSIFICATION	EFFECT ON MOORING OPERATION & PERSONNEL
10	Catastrophic	This includes life-threatening injuries or fatalities, catastrophic damage to the vessel or port infrastructure, and a complete loss of control of the vessel.
9	Critical	severe injuries, significant quay, equipment, or vessel damage, and an inability to control the vessel during crucial manoeuvres.
8	Extreme	The loss of primary function, such as a completely inoperable winch, leads to major disruptions in port operations and poses a risk of near-miss incidents with severe consequences.
7	Major	Degradation of primary function (e.g., winch operating at reduced performance), minor equipment damage, significant operational delay.
6	Significant	Loss of secondary function (e.g., warning lights not working) and minor equipment damage that can be repaired.
5	Moderate	Disruption to operation, minor inconvenience to crew, requires minor repair.
4	Low	There is a minor inconvenience, no impact on the operation, and no damage.
3	Very Low	Minor aesthetic or functional issue.
2	Insignificant	There is no noticeable influence on the operation or safety.
1	None	There is no effect on function or safety.

4.2.2 Fmea Occurrence Scale (O)

The Occurrence rating tells you how likely or how often a certain failure mode will happen. As is often the case in the maritime industry, ratings are based on a mix of past data and expert opinion.

Table 4.14: FMEA Occurrence Scale

RATING	CLASSIFICATION	LIKELIHOOD
10	Almost Inevitable	Failure occurs very frequently, almost every operation.
9	Very High	Failure occurs frequently, more than once per week.
8	High	Failure occurs several times per year.
7	Moderately High	Failure occurs about once per year.
6	Medium	Failure occurs about once every two to three years.
5	Low	Failure occurs about once every five years.
4	Very Low	Failure occurs about once every ten years.
3	Remote	Failure occurs about once every twenty years.
2	Highly Unlikely	Failure occurs about once every fifty years.
1	Almost Never	Failure is extremely unlikely; there are no documented cases.

4.2.3 Fmea Detection Scale (D)

The Detection rating checks how well the current controls can identify the failure mode before it causes a problem. A high rating means that the failure is difficult to identify, while a low rating means that it is easy to locate.

Table 4.15: FMEA Detection Scale

RATING	CLASSIFICATION	LIKELIHOOD OF DETECTION
10	Almost Impossible	Failure is completely hidden or undetectable, with no warning.
9	Very Remote	There is a very low chance of detection.
8	Remote	Chance of detection is poor.
7	Very Low	Chance of detection is low.
6	Low	Chance of detection is low to moderate.
5	Moderate	Chance of detection is moderate.
4	High	Chance of detection is high.
3	Very High	Chance of detection is very high.
2	Almost Certain	Failure is almost certain to be detected before it occurs.
1	Certain	A control or warning system will detect failure with certainty.

4.2.4 Fmea Worksheet For Mooring Operations

The following table displays the FMEA worksheet for a typical vessel engaged in mooring operations. The data is derived from the failure modes and causes outlined in the preceding section, as well as from the responses provided by industry professionals in the questionnaire.

Based on the data encompassing its severity, occurrence, and detection ratings, the Risk Priority Number (RPN) will be determined; $RPN = S \times O \times D$.

Following data collection, the median values for the severity, occurrence, and detection risk scales were calculated before obtaining the RPN. The median was chosen as a measure of central tendency because it is the recommended approach for FMEA analysis, particularly when summarising ratings from a team of experts due to the potential for skewness or the presence of outliers in the severity, occurrence, and detection rating data. The median is less affected by extreme values than the mean (average), resulting in a more representative average value for subjective ratings.

Table 4.16: RPN Calculations

POTENTIAL FAILURE MODE	POTENTIAL EFFECT(S)	SEVERITY (S)	OCCURRENCE (O)	DETECTION (D)	RPN
Mooring line parts under load	Injury/fatality to crew, property damage, collision	9	6	6	324
Miscommunica -tion between bridge and deck crew	Collision, injury, delayed operation	7	5	6	210
Winch brake slippage	Uncontrolled line payout, snap-back risk, collision	8	5	5	200

Lack of clear snapback zone marking	Increased risk of Injury and fatality	7	5	5	175
Incorrect selection of mooring lines	Excessive stress on line	6	5	5	150
Improperly stowed mooring lines	Injury, reduced line life	6	5	5	150

4.2.5 Discussion And Analysis Of Risk Priority Numbers

The Failure Mode and Effects Analysis (FMEA) worksheet, which has a severity rating for very hazardous situations, is a strong and logical way for mooring operations to rank risks. The quantitative assessment examines Severity (S), Occurrence (O), and Detection (D) to identify risks that are excessively high and require proper management.

The evaluation shows that the most dangerous failure mode is “Mooring line parts under load” with a Risk Priority Number (RPN) of 324. This failure scenario fits perfectly into the area of any standard risk matrix that shows unacceptable risk. It has a Severity rating of 9, which means it could kill people or do a lot of damage to buildings and other structures. The concern's Priority Number (RPN) of 324 is much higher than that of any other concern. Therefore, the vessel's safety management system needs to make stopping and controlling unexpected line splitting its top priority. The low average scores for Occurrence (O=6) and Detection (D=6) increase the high RPN. This means that the outcome is not only undesirable but also likely and difficult to guess based on the current measures.

The next group of RPNs, which goes from 200 to 210, shows how difficult it is to connect technical failures to procedural problems. The second primary risk, with a Risk Priority Number of 210, is “Miscommunication between bridge and deck crew”. It ranks high because it has a Severity rating of 7, which means it could cause serious operational problems or injuries, and a Detection grade of 6. The next is “Winch brake slippage”, with a Risk Priority Number (RPN) of 200. The equipment failure has a Severity rating of 8, which means it is a serious safety risk and makes the equipment unusable. There is a chance of unregulated line payout and a snap-back if maintenance procedures aren't followed or the wrong operating methods are used. This shows how important it is to be both technically sound and follow the rules. The high RPN for both misunderstanding and brake slippage shows that safety improvements need to include not only the technical aspects of mooring line materials but also human factors and mechanical maintenance procedures.

There are other ways that things can go wrong besides or before higher-ranked risks happen. For instance, errors can occur, such as “Lack of clear snapback zone marking” (RPN 175), “Incorrect selection of mooring lines” (RPN 150), or “Improperly stowed mooring lines” (RPN 150). It's still critical to lower the risk of catastrophic line failure, even though their RPNs are lower. There are no clear snap-back zone indicators (S=7), which makes queue dispersal more dangerous. This is dangerous for people. Poor line selection and storage, both with a Risk Priority Number of 150, hurt the line's physical properties over time.

The most significant risk of mooring operations is that the line might break, which the RPN of 324 has correctly put at the top of the list. A good risk mitigation plan must be established. First, it must include mandatory technical controls (like tension monitoring) to lower the number of line failures and make them easier to detect. Second, it must address the procedural and maintenance problems found in the RPN 175–210 range to lower the chances of critical technical failure modes happening in the first place.

CHAPTER FIVE

RECOMMENDATIONS AND CONCLUSION

5.1 Recommendations

Based on the study's findings, the following recommendations are presented to enhance the safety and reliability of mooring operations. These recommendations address the high-priority risks identified in the FMEA and integrate them with emerging industry standards and technologies.

5.1.1 Technical And Engineering Recommendations

I. Vessels are required to implement a comprehensive Mooring System Management Plan (MSMP) due to recent amendments to the SOLAS agreement and directives such as MSC.1/Circ.1620.

II. The updated IMO regulations incorporate LDBF, an improved method for predicting line failure. New mooring lines must be certified to comply with LDBF standards, ensuring they will fail at a specified load level within a 5% margin of departure.

III. To mitigate the hazards associated with inadequate line management and excessive tension, vessels should be equipped with real-time tension monitoring systems. Sensors along the lines continuously transmit data to the bridge, informing the crew when loads approach the Safe Working Load (SWL), typically 50–55% of the Minimum Breaking Load for Safe Design (MBLSD).

5.1.2 Operational Recommendations

I. Improve Safety Management Systems. A good SMS must require checklists before starting tasks, set clear rules for how to talk to each other, and make sure that only certain people can get into snap-back zones.

II. Continuous Crew Training. Training must be an ongoing process that teaches crew members how to identify hazards, handle lines correctly, and be aware of their surroundings. Crew members need to know how to spot the risks of being too sure of themselves and understand the physics of mooring lines, such as how synthetic materials can store energy without making noise.

III. Improve deck markings. Snap-back zones and rope bights are very dangerous, so the deck must be clearly marked in these areas. To keep people from slipping and falling, decks must be kept clean and free of oil, grease, and other things that get in the way.

5.1.3 Maintenance and Inspection Recommendations

I. Scheduled inspections. Regularly checking all mooring equipment, such as lines, winches, fairleads, and bollards, for signs of wear, corrosion, and damage.

II. Clear criteria for retirement of mooring lines. It's important to set clear rules for condemning lines based on a physical inspection (like "powdering" between strands or fraying) and their service history (like how many times they've been used).

III. Proper storage of mooring lines. To prolong the life of mooring lines, especially those made of synthetic fibres, store them in dry, well-ventilated areas away from sunlight and chemicals.

5.2 Conclusion

This comprehensive analysis of mooring system failures and risk assessment for commercial vessels in seaports has revealed critical insights into the complex interaction of technological, operational, human, and environmental elements that contribute to marine accidents and inefficiencies. The research indicates that a comprehensive strategy is essential for effective risk reduction. This entails implementing comprehensive Mooring System Management Plans (MSMP) featuring real-time tension monitoring systems, rigorous inspection and maintenance schedules adhering to Line Design Break Force (LDBF) standards, enhanced crew training programmes encompassing technical skills and safety culture, improved communication protocols and snap-back zone representation, and regulatory oversight by agencies. This study offers substantial quantitative evidence to support the marine industry's transition from reactive

to proactive safety management. This demonstrates that systematic risk assessment methodologies, when combined with technological innovation, rigorous regulatory compliance, and human centred operational practices, can significantly reduce the serious safety, economic, and environmental consequences associated with mooring system failures, while concurrently enhancing the efficiency and competitiveness of seaport operations in the global maritime trade network.

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