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Learning from failures: employing fault tree analysis and reliability block diagram to investigate the two deadliest peacetime marine disasters

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Aim: This study aims to investigate the root causes of the MS Estonia and Doña Paz maritime disasters and to derive interdisciplinary lessons that can enhance the safety and reliability of maritime operations. Design/Research methods: The study takes a case study approach and adopts Labib & Read's (2013) framework for learning from failures. This study addresses the following questions: a) What technical factors contributed to the MS Estonia and Doña Paz maritime disasters? b) What human and organizational factors played a role in these maritime disasters? c) How do the reliability and vulnerability of individual components influence the overall safety and failure risk of MS Estonia and Doña Paz? To answer these questions, Fault Tree Analysis (FTA) and Reliability Block Diagram (RBD) techniques are employed. These methods are used to identify a range of technical, organizational, and human factors that contributed to these accidents and to assess the reliability and vulnerability of individual components affecting the safety and failure risk of the vessels.

Conclusions/findings: The analysis revealed that multiple factors, including technical failures, human errors, and organizational shortcomings, contributed to the disasters. The study found that the emergency response and search and rescue systems were particularly vulnerable, where a failure in any component could lead to system-wide failure. Based on these findings, evidence-based recommendations were proposed to enhance safety management practices, regulations, and oversight in the maritime industry.

Originality/value of the article: This study underscores the importance of a systemic approach to learning from failures. It highlights the necessity of addressing technical, human, and organizational factors in maritime safety and provides a framework for future research and improvements in safety management practices. The findings offer valuable insights for maritime organizations aiming to enhance their safety protocols and prevent future disasters.

Keywords: Failure learning, Organizational learning, Fault Tree Analysis (FTA), Reliability Block Diagram (RBD), Marine Disasters, Maritime Safety, MS Estonia, MV Dona Paz
JEL: L92, D81, O33, C63, M48

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1. Introduction

Learning from failure is one of the essential components of increasing safety in an organization (Labib 2014b). Organizations learn lessons from both successes and failures in different manners (Gong et al. 2019). Success stories are seen as proof that existing knowledge functions effectively and supports steady knowledge acquisition (Madsen, Desai 2010). In contrast, failure experiences can trigger a learning process by challenging the status quo and allowing organizations to reflect on existing knowledge, stimulating their willingness to search for new knowledge and providing a clear indication of further development (Gong et al. 2019). Therefore, in comparison to success, failure experiences can produce deeper knowledge about organizational inefficiencies, offer more learning opportunities, and encourage changes in behaviour in response to failures (Baum, Dahlin, 2007).

Failure learning, which produces new knowledge and solutions to lessen the likelihood of future occurrences of accidents, can be a major source of temporary competitive advantages (Cheng, Jiang, 2022). Both operational performance and safety depend on learning from failures; failure learning is required for quality enhancements and productivity gains in production processes, and systematic failure reporting and analyses have been crucial for lowering the number of accidents, e.g., transportation accidents and adverse hospital events (Dahlin et al. 2018). One of the most significant conclusions from the literature on organizational learning is that when organizations gain experience in a field, they tend to perform better in that field, and organizational safety has been shown to follow the same trend of rising organizational performance with rising organizational experience (Madsen, 2009). Haunschild and Sullivan (2002) investigated how past accidents affected future accident rates among major U.S. airlines and discovered that past airline accidents decreased the chance of future accidents for the airline. Since only 32 of the 1,346 accidents in Haunschild and Sullivan's sample involved fatalities, the vast majority of accidents in American commercial aviation are minor, and this finding is consistent with the idea that having experience with minor accidents lowers the likelihood that an organization will experience a minor accident in the future (Madsen, 2009). In a similar vein, Baum and Dahlin (2007) discovered that, in some circumstances, prior accident experience decreased the annual costs of accidents reported by U.S. railways. Many similar studies indicate that prior experience with minor accidents may lessen the possibility that an organization will suffer from disasters in the future, as minor accidents motivate organizations to spend more money on safety programs and motivate employees to be more watchful, both of which may lessen the possibility of future disasters (Argote et al. 2021; Labib, 2014b; Madsen, 2009).

Learning from failures is not a straightforward process and is influenced by various factors. For example, according to Labib (2014) though failures provide a much better learning opportunity than success as they contain valuable information, however, it depends on the organizational ability how to learn from them. Moreover, the effectiveness of learning from failures and mitigating their impact is strongest for recent accidents (Haunschild et al. 2015), accidents of greater magnitude, as measured by accident cost and injury levels (Madsen, 2009), and highly visible events, as indicated by media scrutiny (Desai, 2011). Although early studies of organizational learning curves assumed that all prior experience affects performance in the same way, recent work has shown that the impact of prior experience deprecates over time (Madsen, 2009). Sometimes after an accident or a disaster, resources allocated to safety programs may start to be repurposed (ibid). Recent research has also identified organizational recidivism, which occurs when businesses repeat past errors after learning from failures (Desai et al. 2020). Organizational forgetting and learning discontinuity may occur because information gained from prior mistakes might deteriorate with time and the focus that initially encourages first improvements may wane and move to other areas of interest (Cheng, Jiang, 2022; Holan, Phillips, 2004). In this scenario, businesses run the risk of encountering a disadvantageous situation once more, interrupting the accumulation of knowledge from earlier mistakes (Cheng, Jiang, 2022; Haunschild et al. 2015). Moreover, according to research on organizational learning curves, performance at a focal organization improves as a result of experience at other related or comparable organizations (Madsen, 2009). In this vein, certain research on learning from failures, including that by Haunschild and Sullivan (2002) and Baum and Dahlin (2007), suggests that disasters at other organizations may lessen the risk that a focal organization will also experience a disaster (Desai et al. 2020). Governments and private organizations, therefore, make a great deal of effort to compile lists of disasters that others have experienced and to draw “lessons learned” from them, operating under the presumption that organizations can use these experiences to learn how to prevent disasters from happening to them directly in the future (Madsen, 2009). Even though vicarious learning spares organizations from risky trial-and-error learning and the associated costs of exploration and experimentation, it still poses difficulties that are not present in more direct forms of learning, including making accurate inferences from secondary, incomplete, and complex data and determining the relevance and applicability of such lessons (Valenzuela et al. 2020; Francis, Zheng 2010).

Failure learning is the methodical process of identifying and comprehending the root causes of failures and creating plans to avoid them in the future (Cannon, Edmondson 2005; Dahlin et al. 2018; Desai et al. 2020). Therefore, effective failure learning requires resources to identify and analyze the causes of errors and failures and generate solutions that prevent the same errors and failures from happening again in the future (Dahlin et al. 2018). According to Labib (2014), the process of learning from failures is multifaceted, and its understanding entails a range of related theories. Learning in the context of safety is about feedback that could help develop mental models that, in turn, assist in making better decisions (Labib 2014). Moreover, failures, such as major accidents or disasters, are not merely technological problems but have roots in the broader socio-technical processes and hence their understanding, prevention and mitigation need transdisciplinary methods and efforts (Labib 2015; Stephen, Labib 2018). The traditional focus on learning from failures was on the technical aspects of a system or product, to identify and fix design or operational flaws, however, it is now widely recognized that this approach overlooks the broader social-technical processes, such as communication breakdowns, management decisions, and cultural norms, that contribute to failures (Carayon et al. 2015; Cherry et al. 2021; Klockner, Toft 2018). According to the Sociotechnical System theory, failures frequently originate from an intricate interplay between technical and social elements (Challenger, Clegg 2011). These elements consist of power dynamics, organizational structure, culture, and communication (Aini, Fakhrul-Razi 2010). As a result, failure analysis should also look at elements including legal frameworks, business standards, communication strategies and stakeholder influence on safety practices (Aini, Fakhrul-Razi 2010; Carayon et al. 2015; Challenger, Clegg 2011; Cherry et al. 2021).

Based on the concepts of feedback and mental models in the failure learning process, Labib and Read (2013) have proposed a very comprehensive framework for learning from failures based on three principles: (1) feedback to design, (2) use of advanced techniques for analysis, and (3) extraction of interdisciplinary generic lessons. Failure learning or analysis is the process of gathering and analyzing data to identify the most important factor that contributed to the failure (Farhat 2021). Therefore, it is recommended to use advanced analytical tools to systematically investigate the root causes of failures or accidents (Labib 2014), facilitate effective learning from failures (Labib, Read 2013), prevent future incidents, and implement precautionary measures in advance (Bin Manzoor et al. 2019).

The advanced analytical tools are critical for a thorough and nuanced understanding of failures. A wide range of methods, including Failure Mode and Effects Analysis (FMEA), Failure Mode, Effects, and Criticality Analysis (FMECA), Event Tree Analysis (ETA), Fault Tree Analysis (FTA), Root Cause Analysis (RCA), Reliability Block Diagram (RBD), Human Factors Analysis, Bow-tie Analysis, System Theoretic Accident Model and Processes (STAMP), and Hazard and Operability Analysis (HAZOP), have been developed, each offering unique perspectives and strengths in analyzing failures (Bin Manzoor et al. 2019; Labib 2014). The utilization of these tools enables organizations to understand the complex nature of failures comprehensively (Labib et al. 2019). They address the immediate technical factors and uncover the underlying human, organizational, and systemic issues (Oleo et al. 2024). Employing this systemic approach enhances the capacity to derive actionable lessons, improve designs, and implement robust safety measures, thereby fostering a culture of continuous improvement and resilience (Desai et al. 2020; Grigoriou et al. 2019).

2. The two cases: MS Estonia and Doña Paz

Despite advances in shipbuilding technology, marine disasters still occur, resulting in deaths, environmental damage, and economic losses (Kulkarni et al. 2020; Veiga, 2002). The two cases selected for this report are the Doña Paz and MS Estonia disasters. The selection of these incidents is motivated by their significance as two of the most devastating maritime accidents in history, with a combined death toll of 5,238. The Doña Paz, a passenger vessel, collided with an oil tanker in 1987, causing an explosion and fire that killed 4,386 people (Hooke 1997). The MS Estonia, a passenger ferry, sank in the Baltic Sea in 1994, resulting in the loss of 852 lives (ERR 2023).

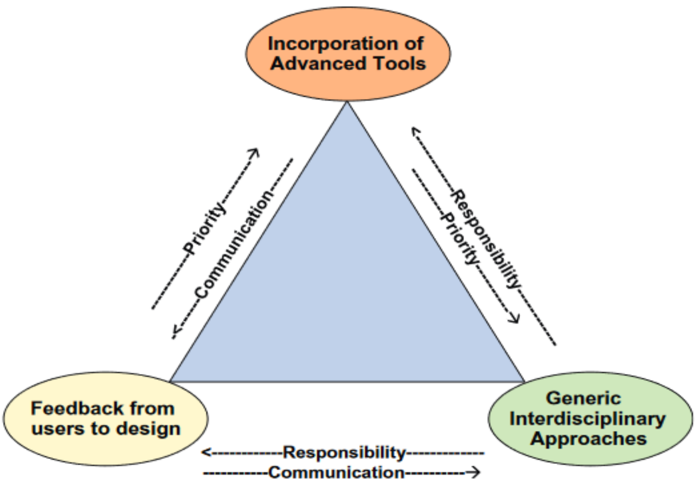
The magnitude and consequences of these disasters highlight the need for a thorough investigation into their root causes. For a holistic understanding of these events, it is essential to explore the interplay of technological, human and organizational factors that could have led to such catastrophic outcomes. Therefore, this study aimed to investigate the root causes of the MS Estonia and Doña Paz maritime disasters and to derive interdisciplinary lessons that can enhance the safety and reliability of maritime operations. This was achieved by answering the following research questions:

- What technical factors contributed to the MS Estonia and Doña Paz maritime disasters?
- What human and organizational factors played a role in these maritime disasters?
- How do the reliability and vulnerability of individual components influence the overall safety and failure risk of the MS Estonia and Doña Paz?
- What interdisciplinary lessons can be learned from these disasters to improve future maritime safety and reliability?

3. Methods

This study took a case study approach and adopted Labib and Read's (2013) framework for learning from failures, as depicted in Figure 1. According to this framework, learning from failure involves: (i) receiving feedback from users (maintenance) to inform design, (ii) integrating advanced analysis tools into creative applications, and (iii) promoting interdisciplinary methods and general lessons (Labib, Read 2013). User feedback helps identify specific failures, leading to analyses that improve system reliability (ibid.). The use of advanced tools such as FTA and RBD helps in identifying and analyzing root causes, allowing lessons to be drawn from failures, and transforming implicit knowledge into explicit knowledge (ibid.). Generic lessons derived from these analyses can be valuable for other organizations and industries and can serve as learning opportunities (ibid.).

Figure 1. Framework of learning from failure



Source: Labib, Read (2013).

This study used two advanced analysis tools: FTA and RBD to identify the root causes of both disasters. FTA is a popular technique for identifying probable paths to system or equipment failure (Yazdi et al. 2023). It is a deductive model that begins with the identification of a top event or failure and then divides the failure's causes into logical paths (Labib 2014b; Yazdi et al. 2023). RBD is a graphical technique used to model the reliability of a system and is sometimes used as a complementary model to FTA (Labib, Read 2015). It is represented as a series of blocks connected in parallel or series form, with each block representing a system component with a failure rate (Labib 2014b).

To identify the root causes, including the human, technical and organizational factors contributing to the MS Estonia and Doña Paz disasters, Fault Tree Analysis (FTA) was employed. The process began with defining the top events (the disasters themselves). Next, FTA systematically broke down these top events into intermediate events and further into basic events (causal factors). Once all possible causes of the top events were identified, appropriate logic gates (AND and OR) were applied to illustrate the causal relationships between the basic events, intermediate events, and the top events. This resulted in detailed fault trees for both disasters, clearly showing all the events and their direct contributions to the top events. Data for both disasters, in qualitative form, were collected from various sources including official reports, documentaries, technical reports, newspapers, internet archives, and witness accounts of the events published in the news or documentaries. However, due to the unavailability of quantitative data, qualitative analysis was used, showing only the minimal combinations of basic events that result in the system failures, i.e., disasters.

To further understand the vulnerability and reliability of individual components contributing to the MS Estonia and Doña Paz disasters, a Reliability Block Diagram (RBD) analysis was employed. The process began by converting the detailed fault trees into RBDs. This involved transforming the basic events (which correspond to components in the RBD) and their configurations (series or parallel) based on the fault tree logic gates (AND and OR). Events connected by AND gates in the fault tree were placed in series in the RBD, indicating that the failure of any one component would result in system failure, while events connected by OR gates in the fault tree were placed in parallel in the RBD, indicating that the system would remain functional as long as at least one component continued to function. Based on the results from the FTA and RBD analyses, a list of technical and managerial recommendations specific to each case was suggested. Additionally, generic lessons were drawn from both cases to aid any industry, particularly the maritime industry, in preventing and mitigating such disasters.

4. Results

4.1. Case 1, the Doña Paz: the deadliest peacetime marine disaster

The MV Doña Paz was a steel-hulled ship built in 1963 with a claimed capacity of 1,518 passengers and a crew of 60 (Perez et al. 2011b). On December 20, 1987, carrying around 4,500 well beyond the declared capacity, a large number of whom were not even listed, the ferry collided with the oil tanker MT Vector in the Tablas Strait in the Philippines (Safety4Sea 2022). The tanker was carrying 1,041 metric tonnes of fuel and other petroleum goods (Perez et al. 2011a). The collision and the explosive cargo onboard the tanker ignited a fire that quickly enveloped Doña Paz, which sank within two hours of the collision (Perez et al. 2011b). It is reported that the Philippine Maritime Authority became aware of the accident after 8 hours and initiated the search and rescue (Perez et al. 2011a).

4.1.2. Causes of the disaster

The official investigation and reports, such as The Maritime Industry Authority (MARINA) Report and The Philippine Coast Guard (PCG) initial investigation, identified the collision between MV Vector and Doña Paz as the main cause of the disaster, with numerous contributing factors including overcrowding, lack of safety measures, and crew unpreparedness (Perez et al. 2011b, 2011a). Some investigations pointed to the already poor condition of the ship due to inadequate maintenance and age, while others suggested that the ship was heavily overloaded beyond its capacity and was listing slightly when departing from the last port (safety4sea 2022).

Another significant cause was the lack of safety culture and regulatory oversight (The Supreme Court of the Philippines 1999). It was claimed that both ships either lacked navigational and communication systems or had faulty ones (Lloyd's Register Foundation 2018). Additionally, the Vector's steering was known to be malfunctioning (Los Angeles Times 1988). Crew members from both ships were not properly trained, and evidence showed that many were negligent in performing their assigned duties (Manila Standard Today 1987; The New York Times 1987).

Another contributing factor was the fire resulting from the ignition of the flammable cargo on the Vector, combined with ineffective firefighting efforts (Hitosis 2019; Safety4sea 2022). Reports indicated a lack of lifeboats and that life jackets were locked away from passenger access (Gunawardene 2012). There were no early warning signals in place to communicate the emergency to passengers, and no evacuation guidance was provided following the collision and fire (Gunawardene 2012; Hooke 1997). Those who escaped the ships were left in shark-infested waters for more than 16 hours (Hitosis 2019). It took maritime officials 8 hours to learn about the accident and another 8 hours to arrange search and rescue operations, which proved futile (Det Norske Veritas 2001).

4.1.3. Consequences

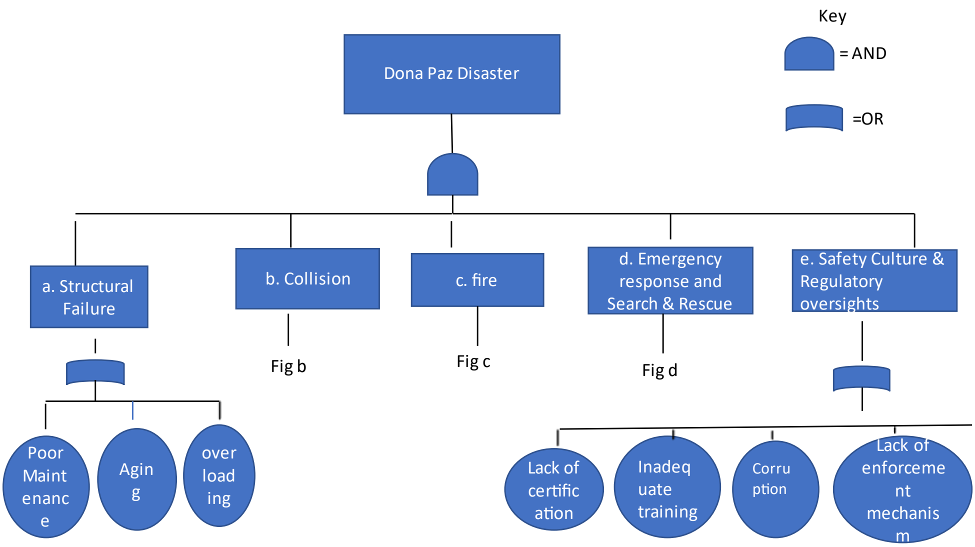
An estimated 4,385 people were killed, including 11 crew members of the Vector (Safety4Sea 2022). Only 26 people were rescued, 24 from Doña Paz and two Vector crew members, many of who sustained major injuries including burns (Perez et al. 2011b, 2011a). The financial cost of the disaster is estimated to be above 100 million dollars (The Supreme Court of the Philippines 1999). Subsequent environmental damage ensued as the Vector was carrying 1,041 metric tonnes of fuel (Safety4Sea 2022). The accident also sparked a debate and various investigations on maritime safety, corruption and accountability.

4.1.4. FTA of the event

The Fault Tree Analysis (FTA) of the event, shown in Figure 2, highlights five main causes that simultaneously contributed to the disaster: a) Structural failure of Doña Paz; b) Collision between Vector and Doña Paz; c) Fire; d) Ineffective emergency response and search and rescue; and e) Lack of safety culture and regulatory oversight. The AND gate indicates that all these factors collectively led to the disaster. The structural failure of the ship may have been due to aging, poor maintenance, and overloading.

Another major cause is the lack of safety culture and regulatory oversight. As the OR gate shows, either the lack of certification for the vessels and crew members, inadequate training of the crew, corruption, or the lack of legal mechanisms to enforce safety standards could have contributed to the deficient safety culture and regulatory oversight.

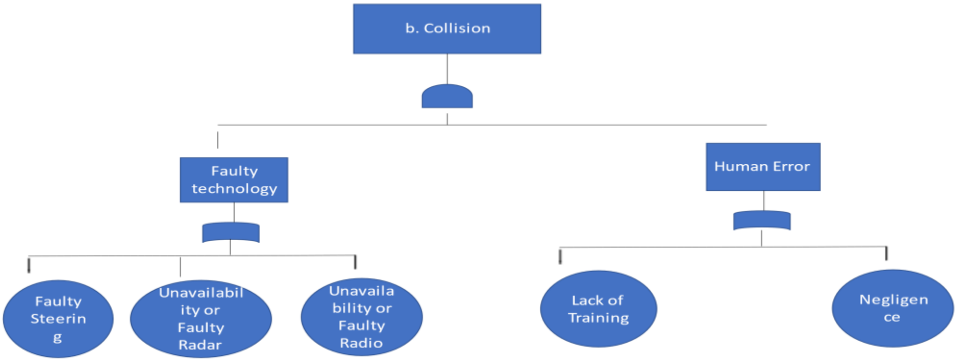
Figure 2. The Fault Tree Analysis of Doña Paz disaster



Source: Created by the author based on data from investigative reports, news reports, and witness accounts.

The FTA reveals that another contributing factor in the accident was its collision with Vector. The collision may have been caused by both technological failures and human error. The AND gate indicates that both factors simultaneously contributed to the collision. As the OR gate shows, either the lack or malfunction of the radio or radar system or a fault in the steering system could have led to the failure of the ship's communication and navigation systems. Moreover, human error may have arisen either due to inadequate crew training or negligence in performing their duties.

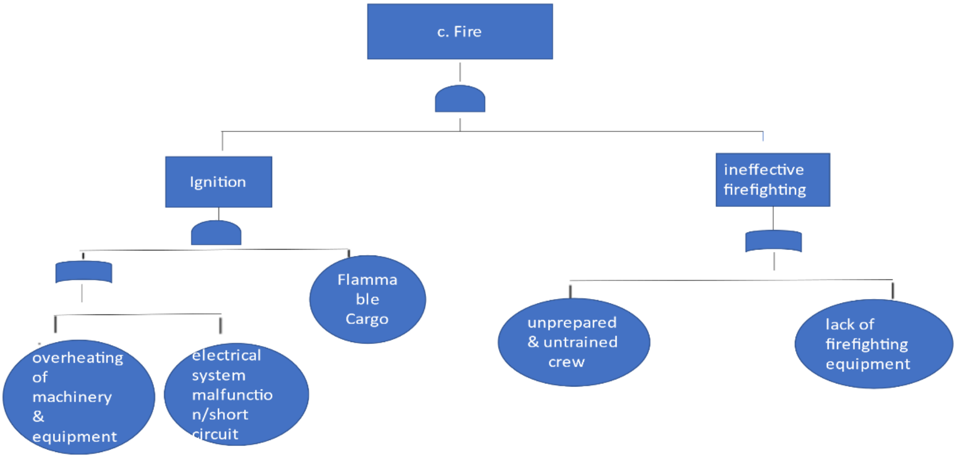
Figure 2(b). The FTA of collision



Source: Created by the author based on data from investigative reports, news reports, and witness accounts.

Another important factor that contributed to the high number of fatalities was the fire. The ignition of the flammable cargo on the Vector, combined with ineffective firefighting efforts, significantly contributed to the disaster. Therefore, both are connected by an AND gate. The flammable cargo may have ignited due to either overheating of machinery or equipment or a malfunction of the electrical system. Once the fire started, the unprepared crew or the lack of adequate firefighting equipment could have resulted in an ineffective fire response.

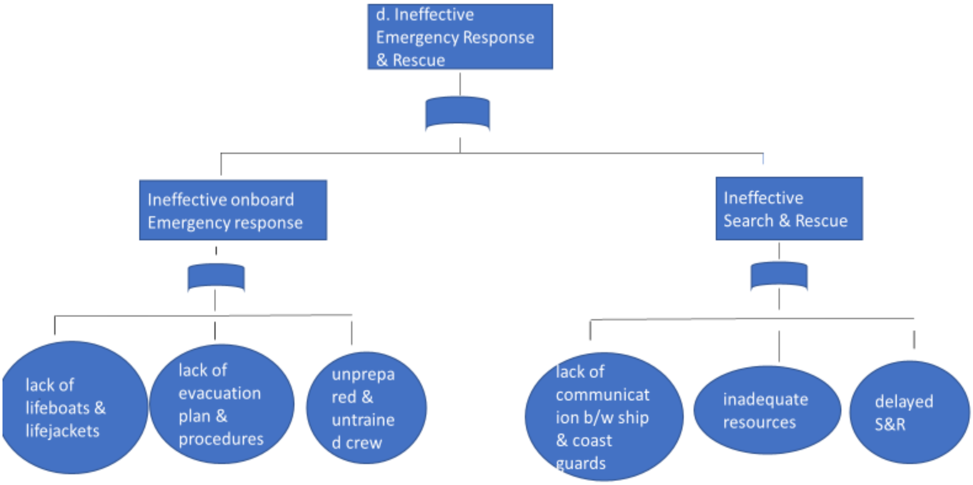
Figure 2(c). FTA of Fire



Source: Created by the author based on data from investigative reports, news reports, and witness accounts.

From the Fault Tree Analysis (FTA), another major factor identified was the ineffective emergency response and rescue. The OR gate shows that either could have resulted in this ineffectiveness. The ineffective onboard emergency response may have been caused by a lack of necessary life-saving equipment, a lack of evacuation plans and procedures, or an unprepared and untrained crew. Moreover, failure in search and rescue could have occurred either due to the ship's failure to communicate a warning to the coast, a lack of proper rescue resources, or a delayed decision from the coast guard to send aerial assets and dedicated marine rescue teams.

Figure 2(d). FTA of Ineffective Emergency Response and Rescue

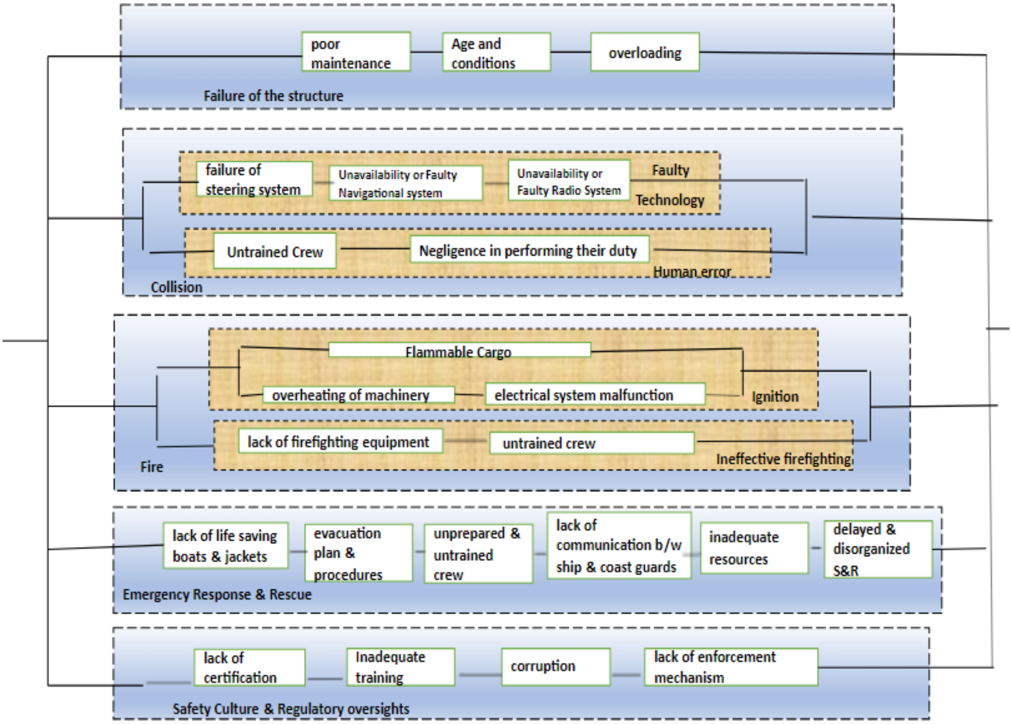


Source: Created by the author based on data from investigative reports, news reports, and witness accounts.

4.1.5. RBD of the event

The Reliability Block Diagram (RBD) of the Doña Paz disaster is shown in Figure 3. This RBD is derived from the Fault Tree Analysis (FTA) for the event, where every OR gate in the FTA is transformed into a series configuration and every AND gate into a parallel configuration. From the RBD, it is evident that the most reliable and redundant systems are those for collision and fire, as most or all of the components must fail simultaneously for these systems to fail. Additionally, the RBD indicates that emergency response and rescue is the most vulnerable system, as the failure of any of the numerous identified components could lead to system failure and subsequent losses.

Figure 3. RBD of Doña Paz disaster



Source: Created by the author based on the FTA of the event.

4.1.6. Recommendations

A. Technical

- Install a more advanced and automated navigation system on the ships
- Install automated communication and early warning systems on the ships
- Install sensors and other smart technologies for load management
- Upgrade emergency equipment such as firefighting equipment, lifeboats, and lifejackets
- Improve and automate maintenance of the ships for testing its various electrical and electronic systems

B. Managerial

- Establish a safety oversight body that enforces safety standards
- Provide regular training and development opportunities to crew members to increase their knowledge and awareness
- Develop and enforce strict cargo loading, unloading and safety measures and procedures
- Develop better onboard emergency management systems
- Improve internal and external communication
- Develop of a sense of responsibility and accountability among the crew members

4.2. Case 2, MS Estonia: Europe's deadliest peacetime marine disaster

MS Estonia was a cruise ferry built in 1980 and used in ferry operations between Finland and Sweden (Lott 2021). Estonia was built on RoRo (roll-on/roll-off) vessel principles, with an upward-opening visor and a car ramp that was placed inside the visor when it was closed (Hooke 1997; MaritimeCyprus 2022). On a stormy night in September 1994, when Estonia was crossing the Baltic Sea en route from Tallinn, Estonia, to Stockholm, Sweden, the ferry sank (Dostal et al. 2015).

4.2.1. Causes of the disaster

According to The Joint Accident Investigation Commission (JAIC) (1997), the primary cause of the Estonia disaster was the failure of the bow visor. The earlier design of Roll-on Roll-off ferries posed significant risks, and this faulty design was a major factor in the European Gateway and Herald of Free Enterprise accidents in 1982 and 1987, respectively (Soma 2020). Many survivors reported hearing a loud bang, and one documentary revealed a 4-meter high and 1.2-meter wide hole in the ferry's hull (Estonian World 2020). However, official accounts state that the bow could not withstand the strain of the water, denying the possibility of Estonia colliding with any other object or explosion (Oltermann 2023).

The official report and other analyses also consider the loss of stability a critical factor in the accident (Det Norske Veritas 2001). According to Whittingham (2004), Estonia was fully laden that night and already had a slight list due to an uneven cargo disposition, which was exacerbated by strong winds. The JAIC (1997) reported that after the bow failure, a large amount of water entered the deck, ultimately causing the ship to capsize. The water not only flooded the deck but also surged through the broken windows and doors, rapidly flooding the cabins and trapping many passengers (Safety4Sea 2019; Whittingham 2004).

No orderly emergency response or evacuation took place in the aftermath of the accident. Many passengers were left trapped in the cabins, and only a few were able to clamber into emergency liferafts (Whittingham 2004). Due to the rapidly developing situation and lack of coordination among the crew, no emergency lifeboats could be launched (ibid). It is estimated that approximately 310 people initially escaped from Estonia, most of whom were left afloat in 11 °C water for around 6 to 7 hours (Brandänge, Gustavsson 2000; Miller 2014). Ultimately, only 138 were rescued (Whittingham 2004).

4.2.2. Consequences

The accident claimed the lives of 852 people, making it one of the deadliest maritime disasters of the twentieth century (Brandänge, Gustavsson 2000). Only 138 people were rescued from the 989 on board, and one of them died later in hospital (Soomer et al. 2001). The financial ramifications of the sinking of MS Estonia were enormous. The public outcry over the accident resulted in a significant decline in cruise ship passengers (Study.com 2023). Several lawsuits and insurance claims were also filed in the aftermath of the accident, with the total cost estimated to be in the hundreds of millions of dollars (BBC News 2020). The disaster also resulted in modifications to passenger ferry laws and safety requirements. The incident also spurred numerous political debates and conspiracy theories (Helsingin Sanomat 2001).

4.2.3. FTA of the event

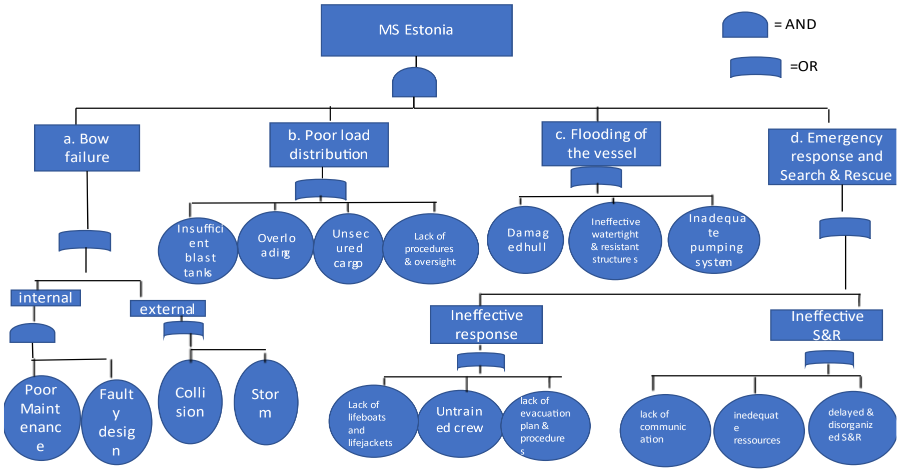
The Fault Tree Analysis (FTA) of the event is shown in Figure 4, where four important factors simultaneously contributed to the incident. These factors are: a) Bow failure; b) Poor load distribution; c) Flooding of the vessel; and d) Ineffective emergency response and search and rescue. The AND gate indicates that all these factors collectively led to the event.

From the FTA, one of the main immediate events identified was bow failure. The OR gate illustrates that either external or internal factors led to this failure. The AND gate demonstrates that both the faulty design of the bow and its poor maintenance simultaneously contributed to its failure. Among external factors, either a collision or stormy weather conditions could have caused the bow to fail.

Another immediate event is the poor distribution of the load. This could have been caused either by overloading of the vessel, unsecured cargo shifting freely during the storm, insufficient ballast tanks that could have compensated for poor weight distribution, or a lack of procedures and oversight that could have prevented poor load distribution, resulting in the ship's loss of stability. Additionally, the FTA identifies another immediate event: the flooding of the vessel. This could have been caused by a damaged hull, ineffective watertight structures such as doors or windows, or an insufficient or faulty water pumping system.

Another major factor identified by the FTA is the ineffective emergency response and rescue. The OR gate indicates that either ineffective onboard emergency response or ineffective search and rescue could have contributed to this. The ineffective onboard emergency response may have occurred due to a lack of necessary life-saving equipment, or a lack of evacuation plans and procedures, or an unprepared and untrained crew. Ineffective search and rescue efforts could have resulted from inadequate resources, or a lack of crisis communication, or a delayed decision to dispatch search and rescue resources.

Figure 4. FTA of MS Estonia disaster

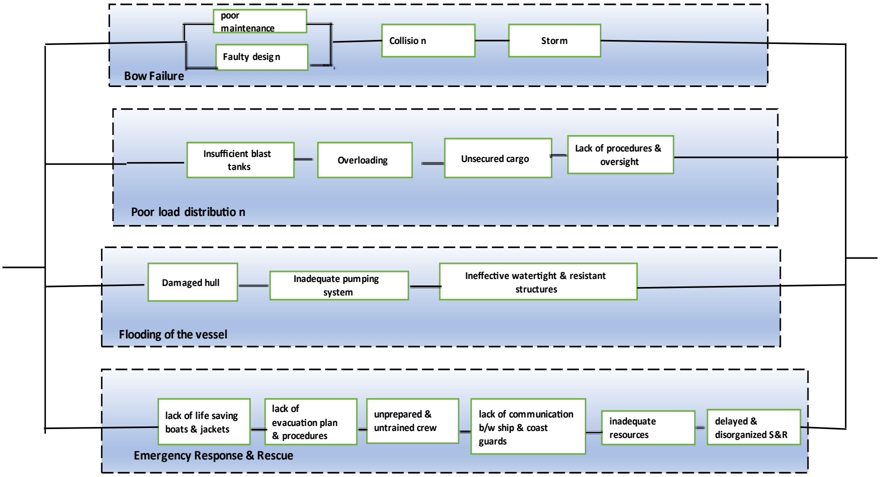


Source: Created by the author based on data from investigative reports, news reports, and witness accounts.

4.2.4. RBD of the event

Figure 5 illustrates the Reliability Block Diagram (RBD) of the MS Estonia disaster. This RBD is derived from the previously discussed Fault Tree Analysis (FTA), where each OR gate in the FTA is transformed into a series configuration, and each AND gate is transformed into a parallel configuration. The RBD reveals that while all systems are susceptible to failure, the emergency response and search and rescue systems are particularly vulnerable. Failure in any of the identified components can result in the failure of the entire system.

Figure 5. RBD of MS Estonia disaster



Source: Created by the author based on the FTA of the event.

4.2.5. Recommendations

A. Technical

- Improve design and construction standards of passenger ferries, especially the redesigning of the bow visor
- Standardise load management on passenger ferries and adopt smart technologies and sensors for load management
- Automate failure detection and early warning system
- Improve safety equipment such as lifejackets and lifeboats on passenger ferries
- Improve communication, coordination, and navigation system of the passenger ferries

B. Managerial

- Encourage onboard safety culture including emergency planning and preparedness and training of the crew

- Establish a coordination body that improves the communication and coordination between the ships and the coast
- Improve the capacity of coastal guards and other marine emergency services so they can effectively deal with catastrophic marine accidents
- Develop SOPs for load management to ensure safety

4.3. Generic lessons

Safety must be prioritized: Based on the analyses of both disasters, we can conclude that safety is an important part of the marine industry. Safety should not be viewed as an added cost or burden, but rather as an integral component of the business. Otherwise, as seen in the examples of Doña Paz and MS Estonia, the consequences are irreversible.

Communication and coordination: Communication and coordination are very critical to avoid or mitigate any accident as we have seen in the case of Doña Paz and MS Estonia. Both breakdowns in communication and coordination, internally among the crew and passengers, and externally among the ferries and coast, made things worse.

Regulation and oversights: They both are a must for avoiding and mitigating accidents and disasters. In both cases, the regulatory and oversight failures allowed both the ferries to sail despite significant safety concerns.

Learning from failure: Both cases demonstrate the importance of learning from failure to prevent and mitigate future disasters. The root causes identified analytically, and the subsequent recommendations, help in learning the key lessons to enhance future safety.

5. Conclusion

Learning is an inherent component of each organization, and organizations learn both from successes and failures. However, failure learning provides more sustainable learning. Failure learning does not happen spontaneously however, and is a very scientific process that requires various analytical tools and models to analyze and understand the root causes of the failure and how to prevent them in the future. Two advanced techniques known as FTA and RBD were used to analyze the two deadliest marine disasters in history.

By applying FTA and RBD techniques to the MS Estonia and Doña Paz disasters, several key factors were identified that contributed to the accidents. These factors included technical failures, organizational failures and human factors. Technical failures included faulty design and structures and poor maintenance, organizational failures included a lack of safety oversight and emergency management and human factors included lack of training and negligence in performing duties.

The strength of FTA for analyzing these disasters is its ability to clearly and logically illustrate the paths leading to system failure. On the other hand, FTA presupposed that events contributing to these disasters are independent of one another, which is not the case. RBD helped in illustrating the reliability of the systems and the systematic connection of each component, either in series or parallel. However, it says nothing about the independence and interdependence of many components in a system. Although these techniques helped identify most of the root causes that could have contributed to these disasters, they still fall short in explaining the complexity and interdependencies among the various factors.

Still, these techniques helped analyze the causes of failures from a highly interdisciplinary perspective. In the case of MS Estonia and Doña Paz, these techniques illuminate that the disasters were not caused solely due to faulty engineering design or quality, but resulted from a myriad of non-technical and managerial decisions and actions, such as the unavailability of emergency and evacuation plans, lack of safety oversight and regulations, inadequate crew training and preparedness, and poor communication and coordination.

After analysis of the root causes, such as in the case of MS Estonia and Doña Paz, evidence-based recommendations were provided that would help in avoiding such disasters in the future. Moreover, the generic lessons learned from such an approach situated the accidents and disasters in the broader socio-economic and organizational processes. This can help organizations evaluate the impact of decisions and choices that are made in the broader socio-economic contexts on the overall safety and resilience of the organization.

In short, by incorporating lessons learned from such a systematic approach to failures, the maritime industry can improve overall safety and resilience and can work toward preventing and mitigating future disasters.

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