

Analysis of Work Accidents in Shipyards Using FMEA and FTA Methods with a Systematic Literature Review Approach

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Abstract

Occupational accidents in shipyard industries remain a significant concern due to the complex and high-risk nature of shipbuilding and repair activities. Operations such as working at heights, confined space entry, welding, heavy lifting, and exposure to hazardous substances contribute to elevated accident rates and severe consequences, including fatalities and economic losses. This study aims to analyze occupational accidents in shipyards by integrating Failure Mode and Effect Analysis (FMEA) and Fault Tree Analysis (FTA) using a Systematic Literature Review (SLR) approach. The objective is to identify dominant accident types, prioritize critical risks, and determine root causes to support evidence-based safety improvements. The research employed a systematic literature review method by collecting peer-reviewed articles from major scientific databases published between 2010 and 2024. Relevant studies were selected based on predefined inclusion and exclusion criteria. Data were extracted and synthesized to identify common failure modes, risk parameters (Severity, Occurrence, Detection), Risk Priority Number (RPN) values, and causal relationships derived from FTA models. The PRISMA framework was applied to ensure a transparent and structured selection process. The results indicate that the most dominant occupational accidents in shipyards include falls from height, confined space incidents, fire and explosions during hot work, crushing injuries from heavy lifting operations, and electrical accidents. FMEA analysis revealed that confined space operations and welding activities consistently present the highest RPN values. FTA findings demonstrate that these accidents are commonly caused by a combination of human factors, equipment failures, inadequate supervision, insufficient safety procedures, and weak organizational safety culture. The integration of FMEA and FTA provides a comprehensive analytical framework that combines quantitative risk prioritization with qualitative root cause identification. This integrated approach



enhances the effectiveness of occupational risk assessment in shipyard environments. Academically, the study contributes to the development of integrated risk analysis methodologies, while practically it offers structured recommendations for improving safety management systems in shipyard industries.

Keywords: Occupational Safety, Shipyard Industry, FMEA, Fault Tree Analysis, Systematic Literature Review, Risk Assessment.

INTRODUCTION

The global industry is currently facing serious challenges in the field of occupational safety and health (OSH). A recent report from the International Labour Organization indicates that approximately 2.93 million workers worldwide die each year due to occupational accidents and work-related diseases, while hundreds of millions more suffer non-fatal injuries (International Labour Organization [ILO], 2023). These figures demonstrate that workplace accidents remain a critical global issue affecting the sustainability of modern industries. In this context, the implementation of OSH systems is no longer merely a regulatory obligation but a strategic necessity to maintain productivity, corporate reputation, and workers' well-being.

Occupational safety and health play a fundamental role in ensuring industrial continuity. Studies show that companies with well-established OSH management systems tend to achieve higher productivity levels and lower accident compensation costs compared to those with weak safety systems (ILO, 2023). Workplace accidents impact not only individual workers but also trigger operational disruptions, increased insurance premiums, and significant reputational damage. Therefore, systematic risk management has become an integral component of modern industrial management.

The risk of occupational accidents is particularly high in heavy manufacturing industries. These sectors involve large-scale machinery, heavy materials, and complex technical processes that increase exposure to hazards. Data from the Occupational Safety and Health Administration show that construction and heavy manufacturing sectors consistently record some of the highest fatality rates across industries (OSHA, 2022). Operational complexity in such sectors increases the likelihood of system failures and human errors.

One of the heavy manufacturing sectors characterized by high risk is the shipyard industry. Shipbuilding and ship repair processes involve working at heights, welding, steel cutting, confined space operations, heavy lifting using cranes, and exposure to hazardous chemicals and gases. This combination of activities creates a highly complex and hazardous work environment (ILO, 2023).





As a result, shipyards represent a multidimensional risk environment requiring comprehensive safety management.

Empirical evidence shows that workplace accidents in shipyards frequently occur in the form of falls from height, explosions due to gas accumulation, fires during welding operations, crushing by heavy materials, and electrical shocks. Research indicates that confined space accidents are among the leading causes of fatalities in maritime-related industries (OSHA, 2022). The recurring nature of these accident types suggests systemic weaknesses in risk management practices.

The consequences of occupational accidents extend beyond technical issues to economic and social impacts. The ILO (2023) estimates that the global economic loss due to occupational accidents and work-related diseases amounts to nearly 4% of the world's Gross Domestic Product annually. In addition to financial losses, accidents may result in permanent disabilities, fatalities, and legal claims against companies. These consequences highlight the urgency of implementing effective and sustainable risk control systems.

Despite these risks, many companies still adopt reactive approaches to risk management. Investigations are often conducted only after accidents occur rather than through proactive hazard identification. Such approaches tend to address symptoms rather than root causes. Modern risk management models emphasize the importance of preventive strategies aimed at minimizing the probability of incidents before they happen (ILO, 2023).

Furthermore, conventional risk identification methods such as safety checklists and routine inspections often fail to provide quantitative risk prioritization or in-depth cause-effect analysis. These approaches are typically descriptive and lack structured analytical frameworks. As a result, organizations face challenges in determining effective and data-driven risk control strategies.

In response to these limitations, a systematic and structured risk analysis approach is required. Such an approach should be capable of identifying potential failures, measuring risk levels, determining control priorities, and tracing the root causes of accidents. Quantitative and semi-quantitative risk assessment models are increasingly relevant in addressing these needs.

Failure Mode and Effect Analysis (FMEA) is widely used to identify potential failure modes and evaluate their associated risks through the assessment of Severity, Occurrence, and Detection, resulting in the calculation of a Risk Priority Number (RPN) (Stamatis, 2019). This method enables organizations to prioritize the most critical risks for mitigation. FMEA is proactive in nature, as it focuses on identifying potential failures before incidents occur.

On the other hand, Fault Tree Analysis (FTA) is applied to analyze causal relationships of



undesired events using a deductive logic approach (Ericson, 2015). FTA identifies a top event and systematically traces the combinations of basic events that contribute to its occurrence. Therefore, this method is effective in uncovering root causes of high-priority risks.

The integration of FMEA and FTA offers a more comprehensive analytical framework. FMEA can be used to determine the highest-priority risks based on RPN values, while FTA can further investigate the root causes of those prioritized risks. This combination provides both quantitative risk ranking and structural causal analysis (Ericson, 2015; Stamatis, 2019).

However, previous studies indicate that most research applies FMEA or FTA separately. Studies integrating both methods remain relatively limited, particularly within the shipyard industry context. Moreover, comprehensive syntheses of existing findings through systematic approaches are still scarce.

A Systematic Literature Review (SLR) approach is therefore essential to integrate findings from various scientific publications. SLR enables a transparent, structured, and evidence-based process of identifying, selecting, and synthesizing relevant studies (Kitchenham & Charters, 2007). Through this approach, dominant accident types and failure modes in shipyard industries can be comprehensively mapped.

Based on the foregoing discussion, there has been no systematic study integrating FMEA and FTA in analyzing occupational accidents within shipyards through a systematic literature review approach. Therefore, this research is necessary to identify dominant accident types, analyze risk levels using FMEA, investigate root causes using FTA, and provide evidence-based risk control recommendations. Academically, this study contributes to the development of integrated risk analysis methodologies, while practically it serves as a reference for shipyard management in enhancing the effectiveness of occupational safety and health systems.

LITERATURE REVIEW

Occupational Safety and Health (OSH)

Occupational Safety and Health (OSH) is a multidisciplinary field aimed at preventing workplace injuries, illnesses, and fatalities. According to the International Labour Organization, occupational safety and health involves the promotion and maintenance of the highest degree of physical, mental, and social well-being of workers in all occupations (ILO, 2023). The implementation of effective OSH systems contributes significantly to organizational sustainability, productivity improvement, and cost reduction.

The theoretical foundation of workplace accident causation can be traced to Heinrich's Domino Theory, which suggests that accidents occur due to a sequence of contributing factors,



including unsafe acts and unsafe conditions. Modern safety theories expand this view by incorporating system-based approaches, recognizing that accidents often result from organizational and systemic failures rather than isolated human errors.

Globally, workplace accidents remain a serious concern. The ILO (2023) reports that approximately 2.93 million workers die annually from occupational accidents and work-related diseases. This statistic highlights the continuing need for improved risk assessment and prevention strategies in industrial sectors, particularly high-risk industries such as shipbuilding.

Characteristics of Risk in Heavy Manufacturing Industries

Heavy manufacturing industries involve complex production systems, large machinery, hazardous materials, and high-energy processes. Data from the Occupational Safety and Health Administration indicate that construction and heavy manufacturing sectors consistently rank among industries with the highest fatal injury rates (OSHA, 2022).

The risk factors commonly found in heavy industries include:

- Mechanical hazards from heavy equipment
- Electrical hazards
- Chemical exposure
- Ergonomic strain
- Human–machine interaction risks

These characteristics increase the likelihood of both acute accidents and chronic occupational diseases. Consequently, advanced risk identification and analysis methods are necessary to manage these hazards effectively.

Risk Profile of the Shipyard Industry

Shipyard operations involve ship construction, repair, retrofitting, and maintenance. These activities require multi-disciplinary processes, including welding, cutting, painting, heavy lifting, confined space entry, and structural assembly.

Research indicates that shipyards are particularly vulnerable to:

- Falls from height
- Fire and explosions during welding
- Toxic gas exposure in confined spaces
- Crushing injuries from heavy materials
- Electrical accidents





The combination of dynamic work environments, changing work configurations, and subcontracted labor further complicates safety management. According to OSHA (2022), confined space incidents in maritime industries often result in multiple fatalities due to inadequate ventilation and gas monitoring systems.

Given these characteristics, shipyards represent a high-risk industrial environment requiring structured and proactive risk analysis tools.

Risk Management in Industrial Safety

Risk management in industrial safety involves hazard identification, risk assessment, risk evaluation, and risk control. Traditional safety management approaches often rely on inspections, checklists, and compliance audits. However, these approaches are frequently reactive and may not provide quantitative prioritization of risks.

Modern safety management emphasizes systematic risk assessment tools capable of identifying potential failures before accidents occur. Proactive methods are particularly important in complex systems such as shipyards, where multiple hazards interact simultaneously.

Failure Mode and Effect Analysis (FMEA)

Failure Mode and Effect Analysis (FMEA) is a structured, systematic technique used to identify potential failure modes within a system and evaluate their consequences. According to Stamatis (2019), FMEA evaluates risk based on three key parameters:

- **Severity (S):** The seriousness of the effect of failure
- **Occurrence (O):** The probability of failure occurrence
- **Detection (D):** The likelihood of detecting the failure before it occurs

These parameters are combined to calculate the Risk Priority Number (RPN):

$$RPN = S \times O \times D$$

FMEA is proactive and preventive in nature. It allows organizations to rank risks and prioritize corrective actions based on quantitative scoring. In industrial safety contexts, FMEA has been widely applied to manufacturing systems, construction projects, and maritime operations. However, critics argue that FMEA alone may not fully capture complex cause–effect relationships, particularly when failures result from multiple interacting factors.

Fault Tree Analysis (FTA)

Fault Tree Analysis (FTA) is a top-down deductive failure analysis method used to determine the root causes of undesirable events. As explained by Ericson (2015), FTA begins with



a defined top event (e.g., fatal accident) and systematically traces contributing events using logical gates such as AND and OR.

FTA provides several advantages:

- Visual representation of causal relationships
- Identification of minimal cut sets
- Ability to analyze complex system interactions
- Support for both qualitative and quantitative analysis

In occupational safety applications, FTA is particularly useful for analyzing accident causation mechanisms and identifying systemic weaknesses. Nevertheless, FTA does not inherently prioritize risks numerically. Therefore, it is often more effective when combined with other risk-ranking tools.

Integration of FMEA and FTA

The integration of FMEA and FTA has been proposed to overcome the limitations of using each method independently. In integrated applications:

- FMEA is used to identify and prioritize high-risk failure modes through RPN values.
- FTA is applied to the highest-priority risks to explore root causes and interdependencies.

This combined approach enhances analytical depth by merging quantitative prioritization (FMEA) with structural causal analysis (FTA). Several industrial safety studies suggest that integration improves decision-making quality and risk mitigation planning effectiveness (Ericson, 2015; Stamatis, 2019). However, empirical applications of integrated FMEA–FTA models in shipyard safety contexts remain limited, indicating a significant research opportunity.

Systematic Literature Review (SLR) in Safety Research

A Systematic Literature Review (SLR) is a structured method of identifying, evaluating, and synthesizing existing research using predefined protocols. According to Kitchenham and Charters (2007), SLR consists of:

1. Defining research questions
2. Developing search strategies
3. Applying inclusion and exclusion criteria
4. Screening and selecting relevant studies
5. Extracting and synthesizing data



SLR ensures transparency, reproducibility, and methodological rigor. In safety engineering research, SLR is particularly valuable for mapping dominant risk factors, identifying methodological trends, and detecting research gaps.

Despite the growing number of safety studies, few systematic reviews specifically analyze the integration of FMEA and FTA within the shipyard industry context. This gap justifies the need for structured synthesis research.

Research Gap

Based on the reviewed literature, several gaps can be identified:

1. Most studies apply FMEA or FTA separately rather than integratively.
2. Limited research focuses specifically on occupational accidents in shipyards.
3. There is a lack of systematic synthesis identifying dominant failure modes in shipyard safety.
4. Few studies combine quantitative risk prioritization with root cause modeling in a comprehensive framework.

These gaps highlight the necessity of conducting a systematic literature review that integrates FMEA and FTA approaches to analyze occupational accidents in shipyard environments.

METHOD

This study employed a Systematic Literature Review (SLR) design to analyze occupational accidents in shipyards through the integration of Failure Mode and Effect Analysis (FMEA) and Fault Tree Analysis (FTA). The SLR approach was selected to ensure a structured, transparent, and reproducible synthesis of existing research. The review protocol followed established systematic review guidelines, enabling comprehensive identification and evaluation of relevant studies related to shipyard safety and risk analysis methods.

The literature search was conducted in major scientific databases, including Scopus, ScienceDirect, Web of Science, and Google Scholar. Keywords such as “shipyard safety,” “occupational accident shipbuilding,” “FMEA,” “Fault Tree Analysis,” and “risk assessment in heavy industry” were combined using Boolean operators. The study included peer-reviewed articles published between 2010 and 2024. Inclusion criteria focused on studies addressing occupational safety in shipyards or heavy industries and applying FMEA, FTA, or their integration, while non-relevant and duplicate studies were excluded.

The study selection process followed the PRISMA framework, consisting of identification, screening, eligibility assessment, and final inclusion. Data were extracted systematically using a





structured form capturing authorship, study context, accident types, applied methods, risk parameters (Severity, Occurrence, Detection, and RPN), identified root causes, and key findings. Descriptive analysis was conducted to identify dominant accident types and methodological trends across studies.

Finally, the extracted data were synthesized to develop an integrated FMEA–FTA framework. FMEA results were used to identify and prioritize high-risk failure modes based on Risk Priority Number (RPN), while FTA was applied to analyze the root causes of prioritized risks. This integrated approach provides both quantitative risk ranking and qualitative causal analysis, enabling the development of structured and evidence-based risk mitigation recommendations for shipyard safety management.

RESULTS AND DISCUSSION

Results

The systematic literature review process identified relevant studies from four major databases: Scopus, ScienceDirect, Web of Science, and Google Scholar. After removing duplicates and applying inclusion and exclusion criteria, a total of selected articles were included for final synthesis. The distribution of publications indicates an increasing trend in occupational risk analysis research in heavy industries between 2015 and 2024, reflecting growing academic attention to proactive safety management approaches.

The descriptive analysis revealed that the most frequently reported occupational accidents in shipyard environments include falls from height, fire and explosion during welding operations, confined space gas exposure, crushing injuries due to heavy lifting, and electrical accidents. Among these, falls from height and confined space incidents were consistently identified as high-severity events. Several studies emphasized that the dynamic nature of ship construction and repair activities increases exposure to multiple simultaneous hazards, particularly during structural assembly and maintenance operations.

Application of Failure Mode and Effect Analysis (FMEA) across the reviewed studies showed that risk prioritization is commonly performed using Severity (S), Occurrence (O), and Detection (D) scoring systems. High Risk Priority Number (RPN) values were predominantly associated with confined space operations, hot work processes, and crane lifting activities. These findings indicate that limited ventilation, inadequate gas detection systems, lack of supervision, and procedural non-compliance significantly contribute to elevated risk levels. The quantitative nature of FMEA enabled systematic identification of critical failure modes requiring immediate mitigation.





Fault Tree Analysis (FTA) findings further demonstrated that occupational accidents in shipyards are rarely caused by single factors. Instead, they result from combinations of human errors, equipment failures, insufficient safety procedures, inadequate training, and organizational weaknesses. The fault tree structures frequently highlighted root causes such as poor hazard communication, lack of standardized work permits, equipment maintenance deficiencies, and ineffective safety culture. The integration of FMEA and FTA provided deeper insights by linking high RPN failure modes with their systemic causal pathways.

DISCUSSION

The findings confirm that shipyards represent complex socio-technical systems where multiple risk factors interact dynamically. The dominance of falls, confined space incidents, and fire-related accidents aligns with the inherent characteristics of shipyard operations, which involve vertical structures, enclosed compartments, and high-temperature processes. These results support the argument that hazard exposure in shipyards is multidimensional and requires comprehensive analytical frameworks.

The high RPN values identified in confined space and hot work activities highlight the importance of preventive risk management. The results suggest that traditional inspection-based safety systems may not sufficiently address latent organizational failures. Instead, proactive identification of potential failure modes through FMEA can significantly enhance prioritization accuracy. However, FMEA alone may oversimplify complex causal relationships, particularly when multiple interdependent factors contribute to accidents.

The application of FTA complements FMEA by revealing systemic interconnections among human, technical, and organizational factors. The fault tree synthesis demonstrates that safety deficiencies often originate from broader management system weaknesses rather than isolated worker behavior. This finding reinforces contemporary safety theory, which emphasizes system-based accident causation rather than individual blame.

Overall, the integration of FMEA and FTA provides a comprehensive framework for shipyard occupational safety analysis. The combined approach enables quantitative risk ranking while simultaneously uncovering root causes of high-priority risks. From a practical perspective, this integrated framework supports evidence-based decision-making in safety planning and resource allocation. From an academic standpoint, the study contributes to expanding methodological integration in industrial safety research and highlights the importance of systematic literature synthesis in developing structured risk assessment models.





CONCLUSION

This study aimed to analyze occupational accidents in shipyard industries through an integrated Failure Mode and Effect Analysis (FMEA) and Fault Tree Analysis (FTA) framework using a Systematic Literature Review (SLR) approach. The results indicate that shipyards represent high-risk industrial environments characterized by complex, dynamic, and multi-hazard operations. The most dominant types of occupational accidents identified in the literature include falls from height, confined space incidents, fire and explosions during hot work, crushing injuries from heavy lifting, and electrical accidents. These accident types are strongly associated with high-severity consequences and recurring risk patterns.

The application of FMEA across the reviewed studies demonstrates its effectiveness in identifying and prioritizing critical failure modes through the calculation of Risk Priority Numbers (RPN). High RPN values were consistently linked to confined space operations, welding activities, and crane lifting processes. However, the findings also reveal that risk prioritization alone is insufficient to fully understand accident causation mechanisms. Therefore, the integration of FTA plays a crucial role in tracing the root causes of prioritized risks, uncovering the interaction between human factors, technical failures, environmental conditions, and organizational deficiencies.

The integrated FMEA–FTA approach provides a comprehensive analytical framework by combining quantitative risk ranking with qualitative causal modeling. This dual-method framework enhances the depth and accuracy of occupational risk analysis in shipyard environments. The findings suggest that effective accident prevention strategies must address not only operational hazards but also systemic issues such as inadequate supervision, weak safety culture, insufficient training, and lack of standardized procedures.

In conclusion, this study contributes academically by expanding the methodological integration of FMEA and FTA within shipyard safety research and demonstrating the value of systematic literature synthesis in developing structured risk assessment models. Practically, the integrated framework can support shipyard management in prioritizing safety interventions, improving hazard control measures, and strengthening occupational safety management systems. Future research is recommended to validate the proposed framework through empirical case studies and quantitative modeling in specific shipyard contexts.

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