International Journal of Sustainability in Engineering, Science and Management
Volume (6) Issue (4) | ISSN:
©IJSESM - APRIL 2026 |pp1 - 22

Doi:

www.ijsesm.org

Review on Effects of Human Error in Machinery Systems Reliability

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ABSTRACT

This review critically examines the impact of human error on the reliability of marine machinery systems. Marine operations have continued to face the challenge of human error in the reliability of their machinery systems despite tremendous advances in sophisticated propulsion systems, computerized monitoring systems, integrated automation systems, and digital alarm systems. Despite the tremendous advances in the field of marine systems, human error is the dominant factor affecting the reliability of machinery systems in the maritime field. It is estimated that human error contributes to between 60% to 80% of maritime incidents. By employing the theories of human error as proposed by various researchers in the field of human factors in the maritime field, including the Swiss Cheese Model of Human Error as proposed by Reason, the Skill Rule Knowledge (S-R-K) Framework as proposed by Rasmussen, Norman's Theory of Action, Dekker's New View of Human Error, and Hollnagel's Functional Resonance Analysis Method, the review seeks to critically examine the concept of human error as a product of various system failures in the operational structures. The review is divided into five chapters. Chapter One defines the research problem by showing that human error in marine machine systems is not a matter of chance but rather a predictable outcome of the interactions between humans, tasks, technology, and organizational factors. Chapter Two conducts a comprehensive literature survey to discuss the theoretical foundations of the research on human error, the unique characteristics of the marine engineering working environment with high temperatures, constant levels of noise, long watchkeeping hours, and psychosocial stressors, as well as the application of the THERP, CREAM, and ATHEANA techniques for the analysis of human error. Chapter Three suggests analytical models for the classification and analysis of human error in marine machine systems by applying the Rasmussen S-R-K framework to classify slips/lapses as skill-based errors, mistakes as rule-based errors, and *knowledge-based errors with examples from the marine industry and the consideration of PSFs and EPCs. Key findings indicate that although skill-based errors occur most frequently, rule-based errors occurring during maintenance activities and knowledge-based errors occurring during troubleshooting pose the greatest long-term threat to machine reliability. Primary causal factors for machine failures include training issues, fatigue from commercial demands and reduced crewing, procedural issues, and design issues. Additionally, the trend of increasing automation in the industry also creates a dual threat by not only reducing workload and error rates but also creating novel failure modes that can contribute to human error, including out-of-the-loop syndrome, automation bias, and opacification. The review establishes that to achieve high reliability in marine machinery systems, a socio-technical approach that incorporates the integration of human factors engineering throughout the entire lifecycle of the ship, from design to construction, operation, maintenance, and finally decommissioning, is necessary. The recommendations include policy improvements to enhance the human element focus of ISM Code audits, fatigue management strategies, investment in simulator-based training, the use of human-centered design, and the creation of tools to apply HRA to marine machinery systems. This review is important to improve maritime safety, efficiency, and environmental protection by providing a framework to understand and mitigate human error in marine machinery systems.*

LIST OF ABBREVIATIONS AND TERMS

Abbreviation	**Full Meaning**
ATHEANA	A Technique for Human Event Analysis
CEG	Course/Program Code (Maritime Safety and GIS Applications)
CREAM	Cognitive Reliability and Error Analysis Method
EPC	Error Producing Conditions
FRAM	Functional Resonance Analysis Method
FSA	Formal Safety Assessment
GEMS	Generic Error Modelling System
GIS	Geographic Information Systems
HFACS-MMO	Human Factors Analysis and Classification System - Marine Maintenance and Operations
HMI	Human-Machine Interface
HRA	Human Reliability Analysis
IACS	International Association of Classification Societies
IMO	International Maritime Organization

ISM Code	International Safety Management Code
LOTO	Lock-Out/Tag-Out
MTBF	Mean Time Between Failures
NZDF	New Zealand Defence Force
PMV-CREAM	Predicted Mean Vote - Cognitive Reliability and Error Analysis Method
PSA	Probabilistic Safety Assessment
PSF	Performance Shaping Factors
SMS	Safety Management Systems
SOLAS	Safety of Life at Sea
SPAR-H	Standardized Plant Analysis Risk - Human Reliability Analysis
S-R-K	Skill-Rule-Knowledge (Rasmussen's Framework)
THERP	Technique for Human Error Rate Prediction

1. INTRODUCTION

In the maritime and marine industries, the machinery systems, including propulsion plants, auxiliary engines, boilers, pumps, steering gears, refrigeration systems, fuel systems, electrical power generation systems, automation systems, and safety systems, have always been considered a backbone in the operation of a ship. The performance of a ship in terms of operation, safety, and commercial success directly impacts the reliability of these systems. (Andrews & Moss, 2002).

According to James Reason (1990), human error has often been a consequence of systemic failures in operation structures and not necessarily a result of human negligence and lack of care. It is found that a high percentage of accidents and occurrences related to machinery in maritime operations are related to human factors. (Ziarati & Ziarati, 2006).

Majority of the maritime accidents, such as the grounding of the Exxon Valdez and the capsizing of the Herald of Free Enterprise, has demonstrated the potential for catastrophic failures due to operational errors, communication failures, and organizational failures (Turner, 1978; Transportation Safety Board of

Canada, 1990). Although these failures are discussed in the context of navigation, similar patterns of human failure can be seen in the operation of the engine room/machinery.

In the maritime equipment system, human error can occur if the installation, commissioning, operation, maintenance, troubleshooting, and emergency response are to be performed in a project. Guttmann and Swain (1983) emphasized the importance of human reliability, stating that it is a quantifiable aspect of system reliability. They emphasized that the risk assessment models should include human reliability, as it is a quantifiable aspect of system reliability. Well-designed mechanical systems can still fail if the human performance constraints are not considered.

Understanding the effects of human error on marine machinery systems reliability is important for improving maritime safety, operational efficiency, and environmental protection when carrying out a project to avoid accidents and incidents.

1.1 BACKGROUND OF STUDY

Over the years and the past century, the maritime sector has witnessed and undergone tremendous and significant growth and development with regards to the technology and equipment used, whereby the modern vessels are installed and equipped with the latest and most advanced systems of propulsion and computerized monitoring and automation systems and alarm systems. The international regulations and the SOLAS Convention were developed by the International Maritime Organization with the aim and objective of minimizing the safety standards with regards to the construction, equipment, and operation of the vessels (International Maritime Organization [IMO], (1974).

Furthermore, the ISM Code has also been developed with the objective and aim of ensuring that the shipping companies implement the same with regards to the Safety Management Systems (SMS), which are designed to cover the operational risks and the human factors (IMO, 2018). However, it has been researched and proven time and again that the human factors have been a major contribution to the maritime accidents and incidents (Reason, 1997). Studies on maritime safety have also revealed and proven that about 60-80% of the accidents and incidents are due to some kind of human error (Ziarati & Ziarati, 2006).

In the engine room operations, some of the major human factors problems are training, fatigue, communication, violation of procedures, and supervision. According to Kletz (2001), accidents happen not due to equipment failure but due to failures in the management systems and the decision-making abilities of humans.

Fatigue has also been recognized as one of the major factors contributing to the degradation of performance in safety-critical industries (Reason, 1997). The personnel working in the engine room have to work in a hot temperature and hot environment with noise and long hours on watch.

Traditional reliability models of reliability engineering have considered failures to result from random mechanical events. However, according to Swain and Guttmann (1983), the assessment of human reliability must be considered along with the assessment of mechanical reliability to arrive at a realistic assessment of the reliability.

With the increased use of automation and digital control systems on modern ships, there is a growing need to understand the relationship between human error and the marine machinery systems to arrive at the reliability outcome.

1.2 PROBLEM STATEMENT

It has also been found that despite the various developments and advancements in the technology of the marine industry, the major reason for the failure of the machinery remains the human error. Even the new ships, which are equipped with the latest machinery, including the automated systems and the reports on the improper maintenance, non-compliance, supervision, and decision-making, the human error remains the major reason.

1.3 RESEARCH QUESTIONS

At the end of the review, the following questions will be answered.

- What types of human error most significantly affect marine machinery reliability?
- What are the primary causal factors influencing human error in engine room operations?
- How does increasing system automation influence human performance?
- What human reliability analysis (HRA) methods are applicable to marine systems?
- What mitigation strategies can improve machinery reliability by reducing human error?

1.4 AIM OF THE REVIEW

The aim of this review is to critically examine the effects of human error on marine machinery systems reliability and to make use of existing theoretical and empirical research to improve understanding of human machine interaction within shipboard and marine engineering environments.

1.5 OBJECTIVE OF THE REVIEW

The objectives of this review are to:

- To identify common types of human errors in the operation of the marine engine room
- To classify the human errors using different established human factors theories and research.
- To examine and analyze the causal factors of the human errors
- To assess and evaluate the effect of human error on system reliability, safety and continuity of operations.
- To propose and recommend mitigation and strategies for improving human reliability in the maritime industry.

1.6 SCOPE AND LIMITATIONS OF REVIEW

1.6.1 SCOPE

The scope of this review focuses on human errors concerning machinery system reliability, which includes engine room operation, propulsion systems, auxiliary machinery, maintenance practices, automation systems, and emergency handling procedures.

1.6.2 LIMITATIONS

The following are the limitations of the review.

- The study relies on secondary sources such as journal articles, investigation reports and theoretical models
- The variations in ship types (tankers, container ships, offshore vessels) may limit the generalization.
- The rapid technological development and growth may render some findings time sensitive
- Quantitative human reliability data specific to marine engineering may be limited compared to aviation industries.

1.7 SIGNIFICANCE OF REVIEW

The significance of this review can be understood through the potential that it holds to contribute to a better understanding of the impact of human errors on the reliability of marine machinery systems. Specifically, the review can contribute to the following.

- **Improving Safety and Reducing Incidents:** The review can contribute to the development of perspectives that can improve the understanding of how the prevention of equipment failures can reduce the causes of accidents, injuries, or environmental risks through the analysis of human errors while operating the engine room. Most marine accidents are a result of human error, as indicated in various research studies (James Reason, 1990; International marine Organization, 2022).
- **Enhancing the Reliability of Marine Machinery System:** Understanding the mechanisms of human error helps the ship operators, engineers, and designers to take proactive measures to reduce the chances of human errors, thereby making the machinery and systems more reliable and efficient. This statement aligns with the Erik Hollnagel (2014) argument on designing systems that anticipate human limitations.
- **Training and Competency Development:** This review would provide the platform for the development of more training programs for the marine engineers, including the training on the various forms of human error and the identification of the causes of the errors, which could help reduce the error rates, as revealed by Rasmussen, J. (1983), through the development of organized training programs on the complex nature of the processes.

2. MATERIALS AND METHODS

Building on the theoretical framework provided this chapter proposes a framework to classify and analyze the causes of human error that impact the dependability of marine machinery systems. The aim is to go beyond the common observation that "human error was a cause" and create a framework that can be used to understand the causes of human error and how they lead to failure, as suggested by the models of Reason and Rasmussen.

2.1 Categorization of Human Errors

There are different ways to classify human errors in the marine environment. Human errors can be grouped based on how people think and act during different steps of a task. The "Skill, Rule, Knowledge" classification of human errors, which the IMO has widely accepted and uses, breaks down human errors into slips, lapses, mistakes, and violations.

2.2.1 Skill-Based Errors: Slips and Lapses

These are mistakes that happens during tasks that are mostly automated and done regularly. Slips happens when someone makes a mistake while doing something, like a simple error in how they carry out a task e.g. Pressing the wrong button is a simple mistake, while lapses are more about forgetting something e.g. They kept forgetting to finish a step. When it comes to machinery reliability, a lapse could be something like forgetting to close a valve during maintenance, which might cause fluid to leak or contaminate the system. The engine room's noisy and busy setting can make these mistakes worse by breaking a technician's focus.

2.2.2 Rule-Based Mistakes

These happen when someone using a rule messes it up or follows a rule that's just wrong. This happens a lot when you're trying to figure out what's wrong. For example, a marine engineer could misread a fault because of a surface-level symptom and end up using the wrong fix, which might cause more damage later on. Not following set rules like Lock-Out/Tag-Out (LOTO) during high-voltage maintenance fits here and can often lead to deadly results.

2.2.3 Knowledge-Based Mistakes

These happen in new situations where the usual skills and rules don't cut it, so the operator has to rely on thinking things through on the spot. Knowledge-based mistakes happen when someone doesn't fully understand how the system works. A good example is when the HMNZS Manawanui sank because the crew didn’t really understand how the autopilot system worked. They didn’t turn it off in time, which caused the ship to run aground.

2.2.4 Violations

Violations are not errors. Violations are wilful deviations from the rules or procedures. Violations can be ordinary events, like cutting corners to save time. Violations can also be unusual events, like taking a chance to get something important done. In engine rooms, people might silence safety alarm horns to stop the constant nuisance of alarm trips. They might silence safety interlocks to keep the machines running. This is obviously bad for both reliability and safety.

Using Rasmussen's S-R-K framework, human errors in marine machinery contexts can be categorized as follows:

Table 1: Categorization of Human Errors Based on Rasmussen's S-R-K Framework

Performance Level	**Type of Error**	**Description**	**Marine Machinery Example**
Skill-Based	Slip / Lapse	Failure of execution or memory during routine, highly practiced tasks.	Slip: Intending to press the "stop" button on the purifier but pressing the adjacent "start" button on a different unit. Lapse: Finishing a maintenance task on a pump but forgetting to re-open its suction valve before starting.
Rule-Based	Misapplication	Correctly or	Misapplication: Following the standard start-

	of a good rule / Application of a bad rule	incorrectly applying a learned rule or procedure to a familiar situation.	up procedure for the main engine, but the procedure is for a different ambient water temperature, leading to thermal stress. Bad Rule: Consistently following an outdated company checklist that omits a critical safety step for boiler light-up.
Knowledge-Based	Mistake	Failure of problem-solving in a novel situation due to incomplete knowledge, flawed reasoning, or cognitive overload.	A complex, cascading failure in the automation system occurs. The engineer, not having experienced this before, misdiagnoses the root cause and attempts a series of incorrect troubleshooting steps, further complicating the problem and delaying recovery.
Violations	Routine / Exceptional	Deliberate deviation from rules	Disabling high-pressure alarm on a purifier to prevent frequent trips

2.3 Causal Factors and Performance Shaping Factors (PSFs)

To analyze why these errors, occur, it is essential to examine the underlying causal factors, often termed Performance Shaping Factors (PSFs). These are the "holes" in Reason's Swiss Cheese model. They can be grouped into four main categories.

Table 2: Analysis of Causal Factors (Performance Shaping Factors)

PSF Category	**Specific Factors**	**Impact on Marine Machinery Reliability**
Person-Related	Fatigue, Stress, Inadequate Knowledge/Skill, Physical Fitness, Morale	A fatigued engineer is more prone to slips during watchkeeping. An engineer with inadequate training on a new automation system may make rule- or knowledge-based mistakes during troubleshooting.

Task-Related	Task Complexity, Procedure Quality (unclear, incorrect, unavailable), Time Pressure, Workload	Overly complex maintenance procedures increase the chance of assembly errors. Unclear alarm logic in a control system can lead to incorrect operator response. High workload during port entry can lead to missed steps in machinery preparation.
Technology/System-Related	Poor Human-Machine Interface (HMI), Ergonomic Design of Controls, Automation Design (opacity, complexity), Alarm System Design (frequency, priority)	Poorly labelled or positioned valves lead to operational slips. An automation system that masks its internal logic makes knowledge-based diagnosis nearly impossible. Alarm floods desensitize operators and cause them to miss critical warnings.
Organizational-Related	Safety Culture, Communication (shift handover, inter-departmental), Manning Levels, Training Quality, Supervision, Work Planning	A weak safety culture discourages reporting of near-misses, allowing latent conditions to persist. Poor handover communication leads to critical information about a developing machinery fault being lost. Inadequate manning leads to chronic overtime and fatigue.

2.4 Human Error Producing Conditions in the Marine Engineering Environment

The marine engine room is a special and challenging working environment. The characteristics of the engine room directly impact the likelihood of human error.

Physical Environment: Marine engine rooms are generally characterized by high ambient temperatures, high noise and vibration levels, and poor air quality. As emphasized by Kletz (2001) and the background study, these environmental conditions can lead to fatigue, decrease performance, and sometimes mimic equipment problems.

Psychosocial Factors: Seafarers often work long hours with long periods of time spent away from home, which can cause stress and social isolation. The hierarchical structure of ships sometimes discourages communication among crew members, especially junior engineers.

Fatigue: This is arguably the most ubiquitous risk factor. The cumulative effect of long working hours, physical strain, noise, and motion sickness affects judgment, reaction times, and increases the probability of slips and lapses. In fact, fatigue was explicitly identified by Reason (1997) as a major risk factor affecting performance deterioration in safety-critical industries, as emphasized in the problem statement of Chapter1.

Watchkeeping and Shift Work: The round-the-clock nature of ship operations requires shift work that affects the body's circadian rhythms and can cause fatigue. Watch handover is a critical period when information on machinery conditions can be lost or miscommunicated.

2.5. Impact on Machinery Reliability and Mitigation Strategies

Human error plays a big role in how reliable machines are because mistakes made during maintenance can cause them to fail e.g. Incorrect reassembly, contamination, and operation errors, like e.g. Overload, cavitation, and troubleshooting, like equipment failures e.g. Cascade failures because of misdiagnosis.

2.5.1 Mitigation strategies

To achieve this, it is important to adopt a comprehensive approach that incorporates human as well as equipment reliability.

- Enhanced Training and Familiarization: This method is referred to as the "Scissors Approach. "The Manawanui case highlights the importance of ensuring that officers receive training that is appropriate for the systems they are working with before they begin working on the vessels, especially where the vessels may have unusual or modified arrangements.
- Engineering Controls: As suggested by the fatality at the Red Stag, the use of locking devices helps ensure that procedures are adhered to, and no one is permitted to access the area without authorization.
- Standardized Procedures and Checklists: Using tools such as checklists for critical operations helps keep things organized, ensuring that nothing is left out. For example, entering confined spaces or handling high-voltage switches helps prevent errors.

- Resilience Engineering: Instead of trying to prevent errors from happening, the system should be designed to respond to errors should they occur.

3. RESULTS AND DISCUSSION

This chapter will synthesize the results from the literature review and the analytical framework chapter to present a discussion of the results. This chapter will specifically answer the research questions through the discussion of the results. This discussion will be a synthesis of the theoretical aspects and the practical aspects using the maritime industry.

3.1 DISCUSSION BASED ON RESEARCH QUESTIONS AND KEY FINDINGS

3.1.1 What types of human error most significantly affect marine machinery reliability?

The literature, along with the categorization in Chapter 3, indicates that slips and lapses, being skill-based errors, are common, but good system design can readily pick up these errors. However, the errors that have the greatest long-term impact are the rule-based and knowledge-based errors, especially the ones involving maintenance.

Maintenance Mistakes: Assembling parts incorrectly, using the wrong parts, or setting the wrong calibration (often rule-based, especially if the wrong procedure is being followed) directly causes failure modes to be introduced into the system. This can cause chain reactions of failures, as well as premature failure of the parts.

Troubleshooting Mistakes: A knowledge-based misdiagnosis of a problem, especially a complex one, can lead to the unnecessary replacement of good parts, wasting time, as well as the failure to fix the problem, leading to repeated failures. The time it takes to recover from these mistakes directly relates to the reliability of the system.

3.1.2 What are the primary causal factors influencing human error in engine room operations?

Moreover, the analysis of PSFs shows and EPC that the major causes of errors are not just individual shortcomings. In fact, the most important causes are:

1. **Inadequate Training (Organizational)**: It is observed that with the increase in technology on ships, proper training is lacking. Engineers are required to operate sophisticated equipment without proper knowledge of how to operate them. Hence, rule-based and knowledge-based errors are guaranteed, as suggested by Ziarati & Ziarati's (2006) findings.

2. **Fatigue (Person & Organizational):** This factor is caused by commercial demands, reduced crewing, and watchkeeping patterns. It is an underlying factor that affects performance at all three levels: skill, rule, and knowledge. This confirms the claims made by Reason (1997) and Kletz (2001).

3. **Poor Procedures/Design (Technology & Organizational):** Inaccurate or missing procedures can be a trap for those at the controls or maintaining equipment, leading to rule-based errors. Inadequate design of control rooms and machinery can cause slips.

3.1.3 How does increasing system automation influence human performance?

Automation, on the other hand, offers a dual role: on one side, it could reduce workload and eliminate skill-based errors by automating tasks, and on the other side, it could introduce new forms of human error, as discussed by Hollnagel (2014):

- **Out-of-the-Loop Syndrome:** When the system automates routine operations, the mental model of the human operator decreases in accuracy. When the automated system fails or cannot handle the operation, the operator must switch to a knowledge-based mode with a poor mental model of the system, which could result in a catastrophic error.

- **Automation Bias and Complacency:** Operators might become too comfortable with the automated system and fail to monitor the system properly, which could cause the operator to miss the symptom of the system failure.
- **Opacification:** An automated system might become too complex, and the operator might not understand the internal workings of the system. When the system raises an alarm due to failure, the operator might not know the reason for the alarm raised by the automated system and might not be able to understand the failure of the system, making it extremely difficult to understand the error.

3.1.4 What human reliability analysis (HRA) methods are applicable to marine systems?

Both first- and second-generation HRA techniques are relevant; however, their applications differ in kind:

- THERP is relevant in quantitative risk analyses, such as those needed in Formal Safety Assessments (FSA) by the IMO, to calculate numerical values of human error probability for a well-defined activity, such as following a checklist.
- CREAM and ATHEANA are more useful in qualitative analysis and in investigating accidents. CREAM's emphasis on control modes and common performance conditions allows a systematic approach to retrospective analysis of an incident or prospective prediction of a high-risk situation in a marine context. CREAM is more relevant in understanding "why" a human error occurred, as in the case of the analysis of causal factors in Chapter 3.

3.2 Synthesis and Implications for Machinery Reliability

The results clearly demonstrate that human error in marine machinery is not a random occurrence but a predictable outcome of the interaction between people, tasks, technology, and organization. For the industry to improve the reliability of machinery, the focus must be removed from apportioning blame to individuals to a more proactive approach to the management of these interactions.

The major implication of this work is that reliability engineering must be a socio-technical discipline. Existing reliability models that only consider the probability of mechanical failure must be combined with human reliability assessments that consider the impact of PSFs. For example, the reliability of a diesel generator set is not just a function of the Mean Time Between Failures (MTBF) but also a function of the quality of the maintenance (dependent upon training, procedures, and fatigue) and accuracy of the operation (dependent upon HMI and watchkeeping).

4. CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

This review essay has thoroughly and critically discussed the impact of human error on marine machinery systems reliability. It has gone beyond the simplistic assumption of human error as individual negligence; instead, it has placed it within the sound theoretical frameworks of Reason's systemic model of human error and Rasmussen's cognitive model of human error. It is confirmed that indeed human error is a ubiquitous factor in influencing machinery reliability.

The main conclusions drawn from this review essay are as follows:

1. **Human Error is Systemic, Not Just Individual:** The root causes of human error are not found in individual negligence, but in latent organizational and technological factors such as poor training, schedules that lead to fatigue, poor procedures, and poor design.
2. **Errors Occur at Multiple Levels:** Errors occurring at the engine room level include skill-based slips, rule-based mistakes, and knowledge-based mistakes. Although skill-based errors are the most frequent, they are the least critical. However, the most critical long-term threat to the reliability of the machinery is rule-based mistakes during maintenance and knowledge-based mistakes during troubleshooting.
3. **Automation is a Double-Edged Sword:** Although automation is beneficial, it has the potential to introduce new routes for human error, such as out-of-the-loop syndrome and automation bias. However, the human interface is the primary factor influencing the reliability of the system.
4. **A Socio-Technical Approach is Essential:** To achieve a marked improvement in the reliability of marine machinery, it is important for the industry to adopt a socio-technical approach. This requires

the incorporation of human factors engineering and human reliability analysis into the entire life cycle of the ship, from design to construction, operation, maintenance, and decommissioning.

In conclusion, it is clear that the achievement of high reliability in marine machinery systems is, therefore, not just an engineering problem but essentially a problem of managing the human element of the system.

4.2 Recommendations

In consideration of the above review, the following recommendations are proposed to improve the reliability of the machinery while mitigating the adverse impact of human error.

4.2.1 Recommendations for Policy and Regulation

1. **Strengthen Human Element Focus in Audits:** ISM Code audits should put more emphasis on ensuring the Safety Management Systems (SMS) being implemented are effective in controlling the causal factors for human error.
2. **HRA in Formal Safety Assessments (FSAs):** It is suggested that the IMO's FSA Guidelines should be updated to include structured HRA techniques (e.g., CREAM) to assess and quantify the risk of human error in critical machinery operations.

5.2.2 Recommendations for Shipping Companies and Ship Operators

1. **Proactive Fatigue Management:** Fatigue management should not be limited to simply complying with hours of work regulations. It should encompass a holistic approach to fatigue management, including education on sleep hygiene, work scheduling in line with circadian rhythms, and a restful shipboard environment.
2. **Investment in High-Quality Training:** Training should not be limited to theoretical knowledge acquisition. It should include high-quality training simulators to allow engineers to "practice" responding to complex fault scenarios (knowledge-based training) and routine operations (rule-based training) in a safe environment, thus directly addressing Rasmussen's (1983) recommendations.

3. **Improve Procedures and Documentation:** Maintenance and operational procedures should always be reviewed and updated. These procedures should be designed in consultation with experienced engineers to make them easy to understand. Procedures should always be available in the local language of the crew members. Procedures should always be made available in a user-friendly format.
4. **Foster a Positive Safety Culture:** A positive safety culture should always encourage the "just culture" approach. Engineers should feel free to report their errors or near-misses without the threat of punishment. This is the only way to learn from mistakes or near-misses. A positive safety culture will always encourage the use of anonymous reporting systems.

4.3 Recommendations for Ship Designers and Manufacturers

1. **Apply Human-Centered Design (HCD) Principles:** Involve marine engineers in the design of the engine rooms, control systems, and HMIs. Ensure the control panel, valve positions, and alarm systems are designed to minimize the possibility of slips while also enabling effective situation awareness.
2. **Design for Maintainability:** Involve the maintainer during the design phase. Ensure easy access to components that need to be frequently maintained. Additionally, design the assemblies to be intuitive for the maintainer to minimize the possibility of slips.
3. **Improve Automation Transparency:** Improve the transparency of the automation system to the operators. Instead of a single alarm for system faults, develop a system where the operators can easily understand the system's actions.

4.4 Recommendations for Future Research

This review has pointed out areas where further research is required:

1. **Empirical Validation of PSFs:** Further empirical studies need to be carried out to assess the specific impact of various PSFs (e.g., fatigue, HMI design) on the error rates of various marine engineering tasks.
2. **Development of Marine-Specific HRA Tools:** There is an opportunity to develop or adapt HRA methods specifically for the unique environment of marine machinery operations. This will result in

the development of a tool that is both rigorous in approach and practical for use in the day-to-day operations of shipping companies.

3. **Longitudinal Studies of Training Effectiveness:** Further research is needed to investigate the long-term effectiveness of different training approaches (e.g., simulator-based training versus conventional training methods) in the reduction of human error and the improvement of the reliability of the machinery systems.

   With the implementation of the above recommendations, the maritime industry will take a significant step toward the goal of zero-harm operations where the reliability of the machinery systems is supported by a deep understanding of the human element.

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