Impacts of Work Stress on Crew Fatigue and Maritime Safety concerning Hazardous Cargo Operations - A comprehensive Review

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المستخلص

فيما يتعلق بالإرهاق، الذي يُعدّ بالغ الأهمية لرفاهية البحّارة الذين ينقلون البضائع الخطرة، فهو ظاهرة تتكون أساسًا من مجموعة من الجوانب المرتبطة بالإجهاد. ومن الواضح أن كل واحدة من هذه النتائج السلبية تؤدي إلى انخفاض مستوى اليقظة الإدراكية، مما يهدد النتائج التشغيلية التي ينبغي أن يحققها العاملون في قطاع النقل البحري. لذلك، تسعى هذه الدراسة إلى تحليل وتنظيم وتلخيص نتائج ٥٦ دراسة، والأطر التنظيمية العالمية، والمنشورات الصناعية المتخصصة. من الناحية الهيكلية، تركز هذه الدراسة على إنشاء أساس نظري بجودة معينة يمكنه تحديد المكونات الرئيسية للإرهاق لدى الأطراف الفاعلة في هذه الصناعة المعقدة. وتتكون من عناصر نظرية وعملية بالإضافة إلى اختبار النظريات، بهدف تحديد المكونات ذات القيمة العملية وأفضل الأطر الارتباطية التي تساعد في تقليل الآثار السلبية لهذه الظاهرة. وتقترح الدراسة طرقًا عملية لمكافحة الإرهاق، باستخدام أنظمة إدارة المخاطر البيومترية (FRMS)، ورعاية الصحة النفسية المناسبة ثقافيًا، والدعم النفسي الموجّه. وأخيرًا، ولمنع الأعباء التنظيمية المفرطة ودعم التكيف مع السياسات القائمة على الأدلة، تدعو هذه الدراسة صناعة النقل البحري إلى وضع معيار للتصنيف يتعلق بالإجهاد والإرهاق.

Abstract:

As far as fatigue is concerned, which is especially important for the well-being of seafarers transporting dangerous goods, is a phenomenon which only consists of a group of numerous stress-related aspects. Clearly, every one of these negative outcomes results in a diminished level of one’s cognitive alertness, thus endangering the operational outcomes which ought to be achieved by employees in the marine transport sector. Thus, this study attempts to analyze, systematize and summarize the results of 56 studies, global regulatory frameworks, and specific industry publications. Structurally, this study focuses on creating a theoretical basis of a certain quality which would be able to outline the principal components of fatigue of the players of this thorny industry. It consists of theoretical and practical components as well as theory testing, in order to identify the key components of practical value and the best correlational frameworks to help reduce the negative effects of this phenomenon. The study suggests practical ways to counter fatigue, using biometric FRMS, culturally appropriate mental health care, and targeted psychological support. Finally, to prevent excessive regulatory burdens and support evidence-

based policy adaptability, this study advocates for the maritime industry to establish a standard of classification pertaining to stress and fatigue.

Keywords: Crew Fatigue, Hazardous Cargo Operations, Work Stress, HAZMAT Operations, Cognitive Fatigue

1. Introduction

The work at hand involves a thorough analysis for a number of 56 peer-reviewed articles, international conventions, and industry reports. The primary objective is to offer a systematic qualitative analysis and uncover primary fatigue drivers in hazardous cargo operations. Employing theoretical frameworks together with empirical research and policy analysis, the current study ascertains that cognitive fatigue in high-stakes operations, such as the management of hazardous cargo, including LNG and toxic chemicals, impairs cognitive functions such as alertness and decision-making. Additionally, it may lead to disasterous consequences by increasing the overall likelihood of accidents. The serious consequences fatigue incurs and its impact on maritime safety have been the focus of attention of numerous investigations related to the maritime sector. Also, several researches have attributed a considerable number of casualties and near-accidents to reduced concentration, delayed responses as well as poor decision-making (Jiandong et al., 2022; Mutignani et al., 2023).

Specifically speaking, fatigue-related hazards become considerably more detrimental in the context of hazardous cargo operations, where even a momentary loss of attention and focus has the potential to trigger a large-scale catastrophe No doubt that historical incidents such as the Exxon Valdez oil spill and the grounding of the MSC Napoli are sufficient examples that can clearly illustrate how fatigue-related human error can trigger large-scale disasterous consequences. Considering such a fact, international conventions, comprising the Standards of Training, Certification and Watchkeeping for Seafarers (STCW) and The Maritime Labour Convention (MLC) have long acknowledged fatigue as one of the foremost safety concerns. Hence, both regulatory frameworks have imposed addressing crucial issues such as minimum rest hours and required fatigue management within the context of training programs (Gadalla et al., 2024). Yet, the proper implementation of all such aspirationshas remained inconsistent and inadequate. In other words, certified evidence confirms and refers strongly to widespread falsification regarding rest-hour records, underreporting of fatigue, inadequate training materials as well as limited oversight from both flag and port administrations (de Larrucea, 2022; T. E. Kim & Gausdal, 2020; KRZYŻEWSKA, 2021). Even the 2010 Manila Amendments, seeking to consolidate fatigue management, so often than not failed to capture the specific mental and emotional strains of risky cargo operation (Praetorius et al., 2020; Yang et al., 2020). More importantly, clarifying terminology with respect to the term fatigue is also of topmost importance for advancing the debate. In fact, work stress has been defined as the psychological strain that may in one way or another occur when job demands exceed available coping demands (Donati et al., 2023).

On the other hand, cognitive fatigue is defined as a measurable deterioration in mental efficiency after sustained cognitive effort (André et al., 2025). These challenges are specifically obvious in high-risk cargo environments, where seafarers confront demanding schedules, limited social interaction and intricate procedures that entail unwavering attention (Yukun et al., 2021). A further complication arises from the rapid adoption of advanced technologies all through the maritime sector. Automation, AI-driven diagnostic approaches, and Industry 5.0 applications are all introduced with the intention of reducing human error, yet these may inadvertently excacerbate cognitive workloads. Hence, operational tasks often shift from direct problem-solving to passive oversight and simultaneous task management, particularly during sensitive phases or periods of reduced activity (Durlik et al., 2025). This contradiction emphasizes the urgency of reevaluating fatigue frameworks within maritime settings, where human error persists in spite of permanent technological advancement. Although considerable evidence acknowledges fatigue as a serious threat to maritime safety, there are notable research gaps that still ought to be sufficiently bridged. A considerable portion of the existing research endeavors is confined to risky cargo handling, vessel-specific duties, and cultural understandings of fatigue. However, numerous serious issues such as the stigma associated with reporting fatigue and the emotional strain of disclosure in high-risk occupations have not been given the due investigation they by all means deserve. Addressing these gaps is crucial for tackling more than just chronic fatigue, which is often exacerbated by the lack of appropriate mental-health aid. In response, the present analysis employs a systematic qualitative review of academic literature, regulatory frameworks as well as empirical findings. Its objectives involve identifying key stressors contributing to fatigue and its operational repercussions, assessing the effectiveness of existing regulations like STCW and MLC on fatigue management and proposing an integrated model that combines technological, psychological and operational perspectives. Further, the recommended framework advocates for task-specific, crew-centered governance supported by cultural competence, biometric monitoring and policy innovation.

2. Research Methodology

A qualitative systematic literature review (SLR) was selected to investigate the links between work stress, fatigue and safety in hazardous cargo operations. The proposed approach was selected because human and organizational elements can best be identified via qualitative means rather than purely quantitative methods. Following the review typology of (Grant & Booth, 2009) and evidence synthesis guidelines by (Tricco et al., 2018), the SLR integrated all findings with theoretical and policy-based literature. Also, the process was aligned with PRISMA 2020 guidelines for systematic reviews (Page et al., 2021), yet adapted for thematic rather than statistical synthesis. Moreover, a regulatory gap analysis was carried out to discern weaknesses in the enforcement of fatigue management and fitness for duty provisions within existing maritime conventions. Also, data collection was implemented across six major Databases-Scopus, Web of Science, Science Direct, Springer Link, Taylor & Francis Online, and Google Scholar, between January and June 2025. Additionally, search strategies utilized Boolean operators to combine terms such as "seafarer fatigue", "hazardous cargo", "mental health", "work stress", "crew alertness" and other references to STCW" OR MLC. From an initial pool of 1,146 records, duplicates were removed prior to applying title and abstract screening, followed by full-text review and eligibility checks. It was only peer-reviewed articles, official reports and convention documents in English published between the years 2000 to 2024 that were included, provided they examined maritime fatigue or hazardous cargo operations involving crew. The entire selection process was documented employing a RISMA flowchart, Figure 1, adapted for carrying out the intended qualitative synthesis.

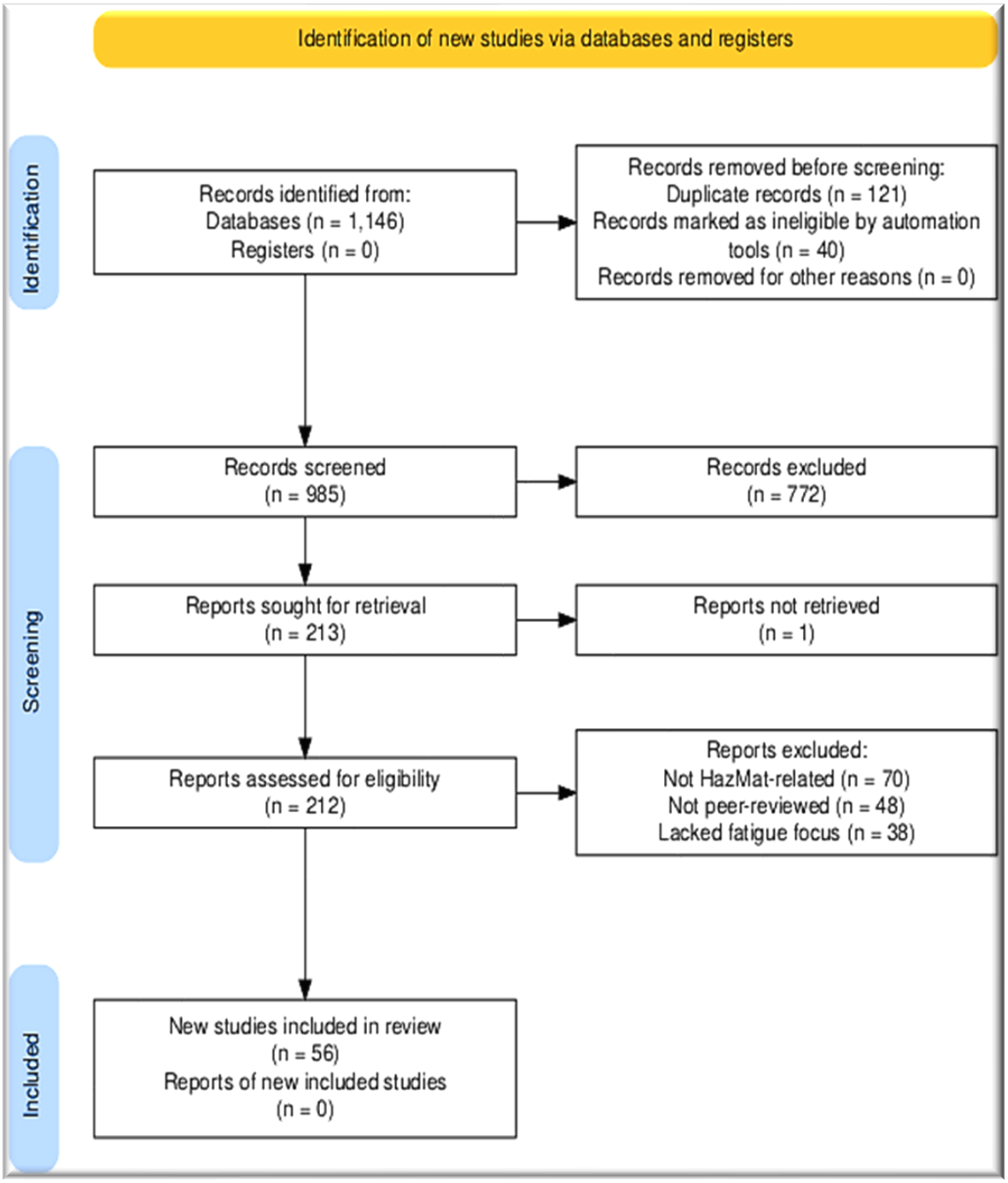

Figure 1. PRISMA 2020 flow diagram of study selection and screening process.

Thematic synthesis was conducted using NVivo 14, a computer-assisted qualitative data analysis software that enables transparent coding, annotation, and retrieval (Bazeley & Jackson, 2013). Coding imparted consideration of the three-stage process of (Thomas & Harden, 2008), with the first stage being inductive open coding, in order to locate granular terms and fatigue constructs present in the studies. Codes were then clustered into axial categories, which were considered broad and encompassing institutional, operational, and psychosocial domains in relation to saturation. Simultaneously during this stage, selective coding derived meta-themes such as regulatory failure, cognitive fatigue, and organizational stress to constitute a conceptual map. An attempt at inter-rater reliability was made by having two independent researchers code the data set, with Cohen's Kappa used as an indicator for the degree of agreement. This was a value of 0.84, which indicates a strong degree of agreement, considering that the closest number ending in 2 reflects this according to (McHugh, 2012). In the interest of transparency toward replicability, all code logs, codebooks, and audit-trails were kept.

A regulatory gap analysis was performed using a custom matrix, Figure 2, inspired by ILO (2019) practices and ISO compliance procedures. This matrix evaluated fatigue-specific provisions of the STCW 2010 Manila Amendments and MLC 2006 for the four dimensions of intent, implementation fidelity, operational limits, and evidence-backed recommendations. So far, the analysis has delved into three highly risky areas, namely the regulation of rest/work hours, the quality of fatigue training, and fitness-for-duty assessments. In these, task-specific fatigue indicators are grossly missing. Findings from a thematic synthesis were mapped against the regulatory instruments to validate gaps and suggest more focused interventions.

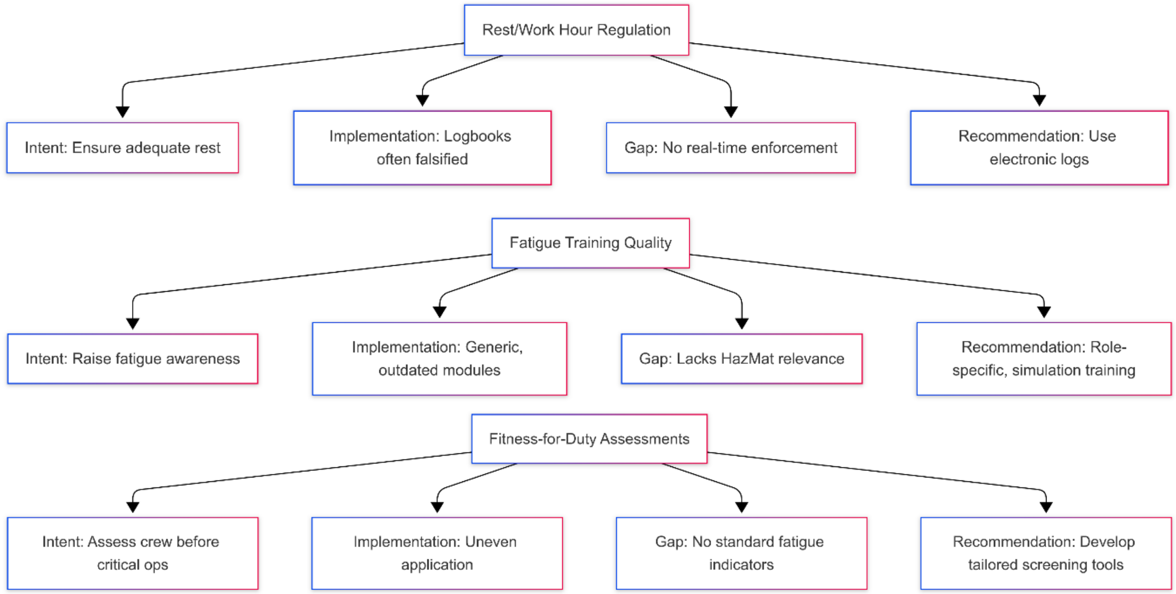

Figure 2. Matrix-based regulatory gap analysis of STCW 2010 and MLC 2006 provisions related to fatigue

Numerous limitations have been encountered and identified during carrying out the current review. Among the most prominent problems is the restriction to English references which led to the exclusion of specific information produced within maritime communities that communicate in other languages or pertain to non-Western regions. Further, the absence of genuine and original data comprising interviews and direct observation has limited the potential of the study to reflect the real conditions pertaining to seafarers. Besides, fatigue may show signs differently according to the vessel category, the crew nationality as well as the range of duties assigned. Notwithstanding, such variations were not systematically categorized within the sources consulted. In order that interpretation bias could be minimized, a reflexive position was maintained throughout the project. Noteworthy that the analytical rigor of the investigation at hand was reinforced via methodological triangulation that combined academic literature, policy reports, industry records as well as structured documentation.

3. Theoretical Considerations

A proper theoretical background is needed to gain a deeper understanding of fatigue and stress within the maritime people and, most importantly, in the high-risk area of hazardous cargo management. The concept of fatigue should be considered as not only a physical issue but also a psychological and organizational one. This section points out the most prominent theoretical models that clarify the ways in which workplace dynamics and cognitive pressures contribute to fatigue and systemic imbalances lead to fatigue in seafaring, with special attention to hazardous material (HAZMAT) handling. The analysis integrates classic occupational stress models with maritime-specific adaptations, forming a conceptual chain from stressor to fatigue to risk (Alsharef et al., 2023; Bazazan et al., 2023; Butlewski et al., 2020).

3.1 Fatigue Scope and Relevant Models

Fatigue in hazardous cargo operations has been given the definition of a multidimensional state of bodily and cognitive depletion that limits and hinders safe and effective task performance (Cunningham et al., 2022; Jiandong et al., 2022). While short-term fatigue may diminish after rest, long-term fatigue shows signs as a result of continuous stressors that prevent recovery, specifically under disturbance of sleeping patterns, prolonged working hours as well as heavy responsibilities. Comparably, occupational stress has been identified as the emotional, cognitive and physical pressure emerging when professional requirements surpass individual resources (Carmona-Barrientos et al., 2020). Cognitive fatigue, considered as a subtype of mental fatigue, occurs as a result of prolonged vigilance and complex decisions, both of which are typical of monitoring activities during hazardous cargo watch. In such a context, stress and fatigue represent a cycle. In other words, occupational stress generates fatigue, fatigue undermines sound judgment and raises the likelihood of mistakes and these errors intensify stress. The aforementioned mechanism is specifically critical onboard ships that transport liquified gas, chemicals and explosive materials. This is mainly because in such circumstances just a single decision may lead to disasterous consequences (Y. Kim & Lee, 2024; Wibowo et al., 2021).

A number of three theoretical models have frequently been applied regarding the interpretation of fatigue within the context of maritime service.

1. Job Demand Control Support (JDCS) Model: According to this model, strain is produced when heavy demands, limited control, and weak social support converge. In maritime practice, continuous vigilance during risky cargo monitoring, rigid procedural frameworks and isolation from social support can generate conditions that are favorable to fatigue. In multinational crews, hierarchical rigidity and cultural divisions further undermine autonomy and cohesion (Jiandong et al., 2020; Whelehan et al., 2021).
2. Effort-Reward Imbalance (ERI) model: In this case, stress and fatigue build up when high effortis not matched with appropriate recognitionor benefit. On chemical tankers, extended work periods, compulsory drills and scarce opportunities for advancement will all combine with low appreciation, generating emotional exhaustion and disengagement (Du et al., 2020; Jeroue et al., 2024; Ménard et al., 2023; Parola et al., 2022; Schulte et al., 2024).
3. Fatigue Risk Management Systems (FRMS): These are particularly applied in high-risk industries. Such systems depend mainly on hazard identification, risk assessment as well as monitoring employing technological and physiological procedures. Also, these systems do not rely on customary fixed working hour rules. Guidelines proposed put forward by the International Maritime Organization in 2019 recommended such an approach for the shipping sector. Yet, implementation has remained partial and inadequately adapted to tasks comprising hazardous materials (Sprajcer et al., 2022).

3.2 Models, Indices and Conceptual Model within Maritime Context

Over the past few years, numerous sector-oriented approaches have also been designed and proposed. The International Maritime Organization Fatigue Guidelines of 2019 introduced a framework that comprised scheduling, rest, environment, health, work requirements, personal factors, as well as organizational practices. In spite of its relevance, limited integration into shipboard safety systems and poor application on the side of flag administrations restricted its effectiveness (Størkersen, 2021). On the other hand, a Seafarer Fatigue Risk Index (SFRI) was introduced by (Sagaro et al., 2023). It integrated biometric information, self-reported sleep quality as well as the exposure to stressors. However, owing to the technological barriers and privacy restrictions, the practical application and use of this index have remained limited.

In order that the reviewed literature could be properly integrated, a conceptual pathway was proposed to trace the movement from occupational stress to fatigue and then to accident risk regarding hazardous cargo operations as pointed out in Figure 3. Noteworthy that the proposed Multi-Layered Fatigue Risk Model is distinguished remarkably from traditional approaches. In fact, what makes it unique is that it stresses real-time data aggregation and adaptive feedback loops. Being so, the recommended approach facilitates testing real-time fatigue monitoring both effectively and consistently.

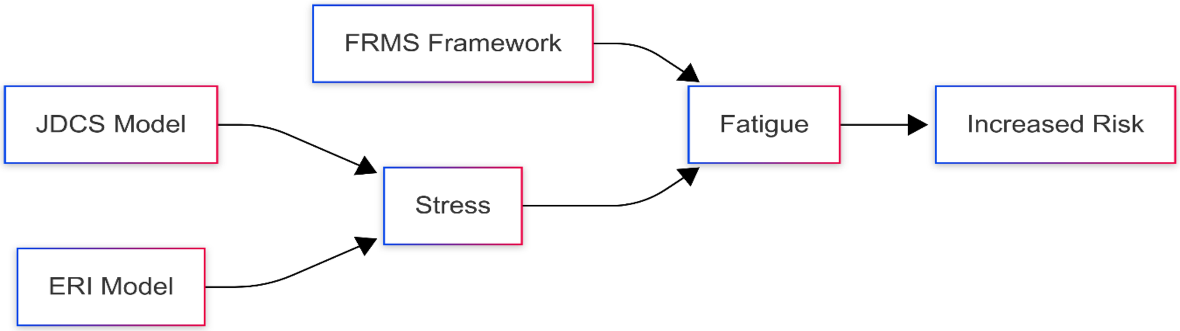

Figure 3. Conceptual chain from stress to fatigue to risk, integrating JDCS, ERI, and FRMS elements within hazardous maritime operations.

The model made it clear that fatigue develops through a nonlinear course that is shaped by multiple systemic impacts. Further, it revealed that risks tied to particular tasks, comprising chemical leakage events or liquefied gas transfer procedures, intensify the demand for predictive and adaptive fatigue management frameworks. In addition, the reviewed models have by all means yielded numerous principal insights. The Job Demand–Control–Support model made it possible to better identify crew members who are confronted by elevated risk resulting mainly from diminishing decision-making freedom and inadequate supportive resources..

Comparably, the Effort Reward Imbalance model revealed problems of morale and decreased motivation among personnel involved in risky cargo handling. In contrast, Fatigue Risk Management Systems provided an operational mechanism for integrating technology with work scheduling. Maritime-oriented instruments involving the International Maritime Organization Fatigue Guidelines and the Seafarer Fatigue Risk Index were revealed to entail wider application and technological reinforcement to support decision-making in real time. Taken together, these perspectives provided a comprehensive framework for the analysis of fatigue from both human and organizational dimensions. These have also clarified the inadequancy of uniform rest-hour regulations and asserted the necessity of context-sensitive and adaptive management for personnel involved in hazardous operations (Jiandong et al., 2022).

4. Review of Empirical Studies

Studies tackling fatigue in seafaring have expanded knowledge regarding the manner in which chronic occupational strain incurs deterioration in performance, breaches in safety and psychological decline, specifically in the field of hazardous material transport. The obtained outcomes from what exceeds fifteen empirical investigations are all organized here under four main themes. These involve indicators of fatigue, hazardous material operational settings, contributing variables and lastly the outcomes related to maritime accidents. On the other hand, the measurement of fatigue among crews has been carried out utilizing physiological, behavioral as well as cognitive parameters. In light of the core of multiple studies, deteriorating fatigue is responsible for the escalation of impairments in alertness, reaction speed, judgment and emotional regulation. As for physiological evidence, it included elevated cortisol, circadian rhythm disruption, and diminished heart rate variability (Cunningham et al., 2022). Cognitive decline was noted in the form of slower reactions, decision fatigue and higher error frequency particularly during watchkeeping (Cunningham et al., 2022).

Sleep-related disturbances such as cumulative sleep loss, fragmented sleep and irregular cycles were frequent, specifically on vessels operated with six-on/six-off watch systems (Hakola et al., 2021). Experimental research employing EEGs and portable devices linked sleep deprivation with impaired executive function and weaker hazard anticipation particularly during training exercises and bridge simulations (Yu et al., 2025).

4.1 HAZMAT Operations as High-Risk Fatigue Zones

Cargo handling involving dangerous substances introduced pressures that were quite distinct from those pertaining to general cargo shipping. These mainly comprised continuous vigilance during liquefied gas or volatile chemical transfer, emergency drills mandated by the International Safety Management (ISM) Code that frequently interuupted rest, and environmental hazards such as toxic exposure, extreme temperatures as well as noise within containment spaces. Officers on watch were obliged to combine mechanical monitoring of pressure, flow and temperature systems with readiness for evacuation or containment in case of leakage, fire, or pressure build-up (Harsono et al., 2025). These accumulated demands created cognitive overload that accelerated fatigue at a faster rate than in container or bulk carriers. Also, reports from hazardous material crews indicated notably higher levels of vigilance stress. This is defined as the mental strain of anticipating rare yet catastrophic events (Alsharef et al., 2023).

4.2 Intrinsic Factors of Fatigue in Seafaring Profession

Research established numerous conditions that generated or intensified fatigue. Extended working hours with insufficient rest were reported on chemical tankers, where officers so often than not achieved fewer than five continuous sleeping hours per day (Sagaro et al., 2023). Sleep disruptioon caused machinery noise, weather, and drills shunned full recovery cycles. Prolonged absence from familyand weak social interaction diminished emotional resilience (Bragazzi et al., 2022). Further, automation led to the reduction of manual work but it resulted in the increase of monotony as well as mental load via passive monitoring, creating apparent decline in vigilance. On the other hand, environmental challenges including vibration, poor air quality, heat stress inside engine rooms or cargo zones led to the deterioration of physical capacity (Guidetti et al., 2023). More important still, Cross-sectional evidence ascertained that mental fatigue, distinct from physical exhaustion, was specifically obvious in hazardous cargo operations and rightly related to job complexity and inadequate recovery periods (He et al., 2025). The serious consequences triggered by fatigue-related factors have long been a major concern in the maritime sector. Indeed, numerous major maritime catastrophes were connected to crew fatigue and excacerbated by operational and systemic stressors.

- Exxon Valdez (1989): The oil spill was associated with fatigue after prolonged working hours, communication breakdowns, and delayed judgment. The officer on duty had remained awake for more than eighteen hours (Harrald et al., 1990).
- MSC Napoli (2007): The UK Marine Accident Investigation Branch (MAIB) reported fatigue as a contributing factor leading to the failure of a vessel and the loss of cargo as a consequence. Concerns about fragmented sleep and insufficient staffing had been expressed by the chief engineer (Talley et al., 2005).
- Chemical Tanker Incidents: A European Maritime Safety Agency (EMSA) review of 212 accidents including hazardous material tankers between concluded that 46% were associated with cognitive errors linked mainly to inadequate rest as well as minimized vigilance during essential tasks comprising valve sequencing and inert gas monitoring. Also, simulated exercises indicated that fatigued crews reacted 30 - 40% more slowly in emergency shutdowns than well-rested crews (Ammar et al., 2023; Barr et al., 2009; McCulloch et al., 2012).

4.3 Fatigue Risk vs Vessel Type

Noteworthy that the analysis pertaining to sleep patterns, reaction times, and error rates across vessel categories, Figure 4, indicated heavier fatigue among chemical and liqefied gas crews owing to complex and hazardous operations (Huerte et al., 2023). Additionally, chemical tanker personnel averaged 5.2 sleeping hours, a 14 % error rate and reaction times of 420 milliseconds. Also, LNG carrier crews recorded 5.5 hours of res, a 12% error rate and reaction times of 410 milliseconds. Comparably, the crew related to bulk carriers and containers averaged 6.5 and 6.8 hours of rest, error rates of 8% and 7%,, and reaction times of approximately 390 ms and 380 ms respectively (Bilir et al., 2023). The dangers related to fatigue symptoms in the maritime sector are still posing a real threat to the sustainability and reliability of maritime activities up till now. Again, recent incidents continue to demonstrate the severe repercussions of fatigue on seafarers and maritime safety. For instance, on 22 May 2025, the general cargo ship NCL Salten grounded near Trondheim, Norway, after the watchkeeping officer reportedly fell asleep during duty (ABC News, 2025). Similarly, the IMO Maritime Safety Committee (MSC 110), which convened from 18–27 June 2025, emphasized the necessity for stricter adherence to work–rest hour criteria and recognized fatigue as a permanent hazard to maritime safety (IMO, 2025). Also, the INTERCARGO Bulk Carrier Casualty Report 2025, issued in May 2025, made it quite apparent that countless bulk carrier groundings and losses up to 2024 were triggered by human error, with fatigue identified as a probable contributing element (INTERCARGO, 2025). Another tragic example took place at Mesaieed Port, Qatar, in the summer of 2023, when one seafarer passed away and numerous others collapsed owing to intolerable heat and exhaustion. That catastrophe was reported by the Nautilus Federation in 2024 and it just adds more emphasis to the fact that environmental pressures can seriously complicate and intensify fatigue (Nautilus Federation, 2024). Furthermore, the abandonment of more than 3,000 seafarers across 230 vessels in 2024 left crews extremely overworked, unpaid, and liable to massive mental and physical strain (AP News, 2024). Overall, these incidents refer strongly to the urgent need for adequate and effective fatigue-mitigation frameworks within the maritime industry.

Again, all of the acquired findings add even much more weight and credibility to the evidence that hazardous cargo operations lead to remarkably heavier workloads. This is largely due to the fact that such duties require uninterrupted alertness, abidance by stringent procedures and liability to extreme environmental conditions. All these detrimental factors will ultimately result in the escalation of fatigue levels (Eliopoulou et al., 2023; Kashevnik et al., 2024). More important still, fatigue is not merely the result of insufficient rest. In fact, it is a complex, multifaceted condition that is much influenced by cognitive overload, demanding tasks, and broader systemic pressures (Mahdavi et al., 2024). Existing approaches to fatigue assessment, involving rest-hour documentation and self-reported evaluation, have been shown to be unreliable or even manipulated (Herzog-Krzywoszanska et al., 2024). This reality emphasizes the pressing need for continuous and objective monitoring systems. On the other hand, novel approaches, comprising wearable physiological sensors, artificial intelligence-based prediction models as well as fatigue-risk platforms, were all asseted to be quite promising tools for individualized and continuous evaluation concerning seafarer fatig (Kyriazis et al., 2025; Watterson et al., 2023).

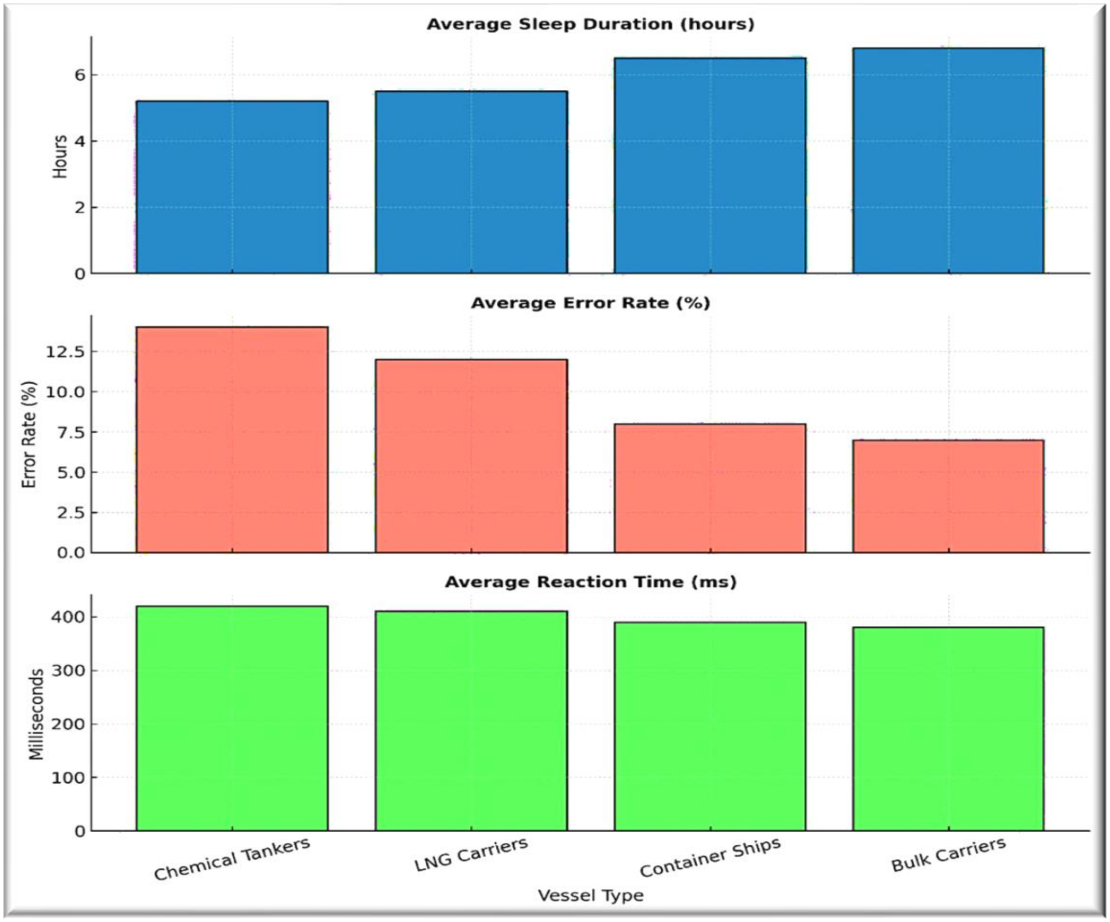

Figure 4. Comparative fatigue indicators across vessel types.

5. Gap Analysis based on Regulatory Review

International frameworks including the 2010 Manila Amendments to the STCW Convention and the Maritime Labor Convention of 2006 (MLC) were essentially meant to manage seafarer fatigue. The enforcement of these regulatory frameworks regarding hazardous cargo operations has nevertheless remained uneven and insufficient. The current section is basically intended to assess these tools and to help better identify mismatches among their provisions and actual maritime practice. Further, it sheds light on the foremost shortcomings reported in empirical investigations. Moreover, it provides a gap analysis matrix with view to connecting the stated intentions of regulation with practical deficiencies and recommending evidence-based adjustments.

5.1 Essential Provisions pertaining to STCW and MLC Fatigue

Noteworthy that the 2010 Manila Amendments to the STCW offered specific requirements under Regulation VIII/1 and Section A-VIII/1 regardingwork and rest periods, watchkeeping arrangements as well as fatigue prevention. These requirements comprised all of the following considerations:

- A minimum of ten hours of rest during any twenty-four-hour period.
- At least seventy-seven hours of restduring any seven-day period.
- Watchkeeping schedules that are coherent with circadian principles.
- Training on fatigue awareness based on International Maritime Organization model courses.

It is also important to note that The MLC 2006, often described as a charter of rights for seafarers, added complementary measures that entailed all of the following:

- Defined rest hours as well as limitations on working periods.
- Adequate ship manning levels.
- Access to medical services, comprising support for mental health.
- A policy framework for occupational health and safety, including fatigue-related risk management.

It is also necessary to note that both conventions depended on a prescriptive system that is focused on documentary evidence involving rest-hour logs and watchkeeping records. As previously pointed out, this system was demonstrated to be quite vulnerable to manipulation and so often failed to reflect the actual circumstances encountered during hazardous material operations.

5.2 Inconsistency between Regulation and Reality

In spite of the detailed provisions of STCW and MLC, significant discrepancies have been observed and recorded between regulatory obligations and operational realities, specifically on ships involved in hazardous cargo service. Rest-hour records were repeatedly altered, particularly on tankers operating with limited manning or compressed timetables (Tang et al., 2022). Also, training on fatigue was provided in a general form, without adaptation to various scenarios including liquefied gas transfers or reactive chemical handling. More important still, both of fatigue and mental health were tackled as separate issues in the MLC, although evidence has adequately demonstrated their interdependence. In addition, watchkeeping schedules were often arranged without regard to circadian rhythm science, with personnel placed on duty during biological low points between 0200 and 0500 hours. To add, no requirement was included for the use of real-time fatigue monitoring tools, despite the availability of biometric equipment and artificial intelligence-based alertness assessments. Also, Flag State control was applied inconsistently, and Port State control inspectors lacked access to real-time fatigue information. An evident shortcoming that results in weak enforcement. More importantly, in order that the divergence between intended regulation and observed practice could be discerned, a structured gap analysis matrix, Table 1, was produced. It is a framework that links specific regulatory provisions with implementation failures. Further, it outlines potential corrective actions that could strengthen fatigue management in hazardous cargo operations.

Table 1. Regulatory gap analysis matrix

Provision	Intended Function	Observed Limitations	Recommended Improvements
STCW – Rest Hours	Prevent fatigue via minimum rest periods	Widespread falsification of rest-hour records; non-task-specific	Implement automated rest monitoring; enforce audits
MLC – Fitness for Duty	Ensure crew are medically and psychologically fit for duties	Infrequent assessments; mental health often overlooked	Integrate routine psychological evaluations; define clearer diagnostic thresholds
STCW – Fatigue Training	Educate seafarers on fatigue awareness and management	Content too general; lacks specificity for hazardous cargo handling	Design role-specific training modules for high-risk operations and hazardous materials

5.3 Enforcement, Structural Hindrances and Beneficial Guidelines

Versatile structural obstacles have hindered the effectiveness related to fatigue regulations in maritime operations. These can be illustrated as follows:

- **Flag State and Port State Enforcement:**
  Flag states have been assigned primary responsibility for monitoring compliance and adherence, yet many have operated with limited resources and, in certain cases, with incentives to underreport violations. Also, Port State Control has provided a secondary layer of oversight, however inspections have remained superficial owing to restricted time as well as the absence of access to biometric or onboard observational data.

- **Cultural Barriers:**
  Multinational crews often serve within hierarchical systems where mental health and fatigue carry stigma. Consequently, many seafarers fail to report fatigue to avoid being perceived as weak or non-compliant (Onakpojeruo et al., 2023).

- **Lack of Technological Integration:**
  Existing regulations were in the first place merely designed for paper-based compliance systems. With the introduction of digital logbooks, wearable devices and fatigue-detection innovations, regulatory frameworks have not yet incorporated such novel technologies into mandatory safety management practices.

- **Training gaps:**
  Although STCW mandates training on leadership and fatigue, most curricula have overlooked realistic stressors regarding hazardous cargo operations including late-night valve transfers, toxic exposure drills as well as chemical leakage simulations.

Based on the derived outcomes of the empirical literature, it is recommended to carry out a transition from reactive to proactive fatigue management. This is specifically so crucial when it comes to tankers and liquefied natural gas carriers. Thus, a number of measures are recommended and these comprise all of the following:

- Mandating the application of real-time fatigue monitoring employing wearable sensors and cognitive alertness assessments.

- Digitalizing rest-hour logging and incorporating biometric feedback into Safety Management Systems as well as International Safety Management Code audits.

- Integrating fatigue modules that tackle and address hazardous material operations into mandatory STCW training courses.

- Embedding Fatigue Risk Management System (FRMS) criteria and principles into shipboard management strategies and plans and designating fatigue officers on vessels with elevated risk profiles.

The current international framework has yielded a minimum baseline but has not accounted for the operational complexity and elevated fatigue exposure concerning hazardous cargo handling. The prescriptive structure pertaining to STCW and MLC has remained inadequate in contexts where performance demands frequently outweigh compliance incentives. Hence, a more adaptive technology-supported , and culturally sensitive regulatory model is essential. The required model ought to handle fatigue as a systemic safety hazard rather than a matter of individual endurance.

6. Thematic Analysis

A qualitative synthesis of 68 reviewed sources helped identify four dominant themes that describe the interaction pertaining to work stress and fatigue in hazardous cargo operations. All these themes were acquired via repeated coding of empirical outcomes, policy reviews as well as theoretical applications. Further, these were validated within maritime-specific-contexts involving chemical tanker operations, LNG transfer watch keeping and confined-space maintenance.

6.1 Key Sources of Operational Fatigue

Operational fatigue results mainly from physical exhaustion and circadian disruption associated with working time structures, duty cycles as well as demanding tasks. It shows signs in hazardous cargo contexts where crews frequently follow six-on/six-off shifts, participate in drills during rest hours and carry out cargo transfers entailing continuous vigilance for prolonged periods. Also, rest has been further disturbed by environmental stressors involving noise, vessel motion and weather. In light of the conducted empirical research, seafarers onboard hazardous cargo vessels obtained an average of 4.7 hours of sleep daily, with measurable increments in cortisol levels as well as impaired short-term memory (Hakola et al., 2021). Furthermore, Cognitive fatigue differs from physical exhaustion by originating in sustained attention, complex decision-making as well as information overload. Further, it manifests as delayed alarm responses, difficulty interpreting risk thresholds and minimized hazard perception. It usually triggers vigilance stress, monotony in system monitoring and sleep inertia. Comparative simulation studies asserted that hazardous cargo crews exhibited reaction delays of up to 40% longer than non-hazardous cargo crews during valve failure drills (Chan et al., 2020; Sharma et al., 2023).

6.2 Fatigue incurred by Organizational and Cultural Stressors

Within the framework of organizational and cultural norms, fatigue is so often than not treated as an individual weakness rather than a systemic concern. Hence, subthemes include the prioritization of ship operation over crew welfare and well-being, unwillingness to speak out fatigue owing to stigma as well as communication hinderances within multinational crews. Despite the fact that the MLC has provisions for mental health support, enforcement has remained uneven. Also, many seafarers are oblivious to the fact that they have the right to decline duty if they suffer from fatigue symptoms. On the other hand, technological underutilization has been acknowledged as one of the foremost persistent shortcoming regarding fatigue management. Further, the majority of vessels still rely on rest-hour records that do not necessarily represent lived experience. On the other hand, few among them have fostered objective monitoring systems comprising wearable devices, EEG-based measures or artificia intelligence integrated into Safety Management Systems. Various trials in related industries have revealed that predictive fatigue models can predict lapses up to 20 minutes before the ultimate failure. Notwithstanding, such tools have not so far been carried out in maritime operations (Mcnamara et al., 2023). The four themes are interrelated in a systemic chain, Figure 5. Insufficient organizational practices and cultural hinderances reinforce technological limitations. Such shortcomings will ultimately incur operational fatigue, which in turn amplifies cognitive strain in hazardous environments. The displayed sequence can just illustrate how fatigue develops as a multi-level safety risk rather than an isolated physiological phenomenon.

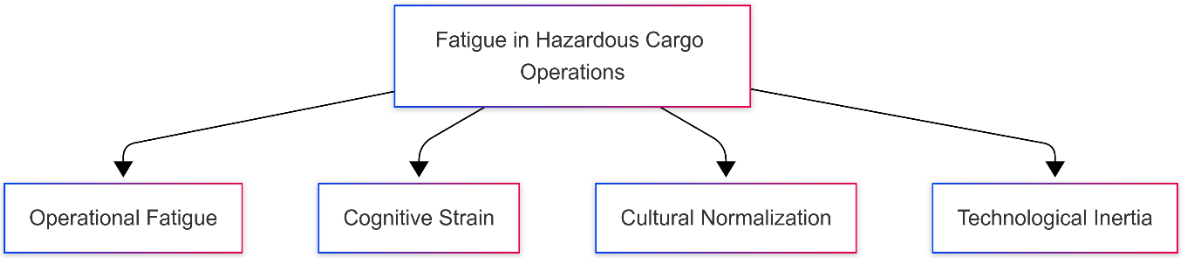

Figure 5. Thematic analysis of fatigue in hazardous cargo operations

7. Future Directions in light of the current research gaps

It is true that the number of investigations that are focused on fatigue in hazardous maritime operations is continuously on the rise. Additionally, the regulatory frameworks assigned for the same purpose is also regularly updated. Notwithstanding, the full dimensions of fatigue sources and consequences remain undermanaged in several crucial areas. The following section will shed light on the most prominent gaps that hinder the effectiveness of current approaches. Further, it points out a multi-dimensional framework with view to guiding future research as well as systemic reform. More importantly, existing empirical evidence largely stems from cross-sectional surveys or short-term simulation investigations. However, longitudinal research that tracks fatigue accumulation, recovery dynamics and decision-making performance across heterogeneous voyages and vessel types is still scanty and scarce. For instance, chemical tankers and LNG carriers operate under distinctly various routines, yet there are no large-scale comparative datasets that account for or capture their long-term fatigue patterns. Current assessments generally depend solely on generic seafaring indicators involving rest hours or self-reported tiredness. All these factors will ultimately fail to reflect the unique demands of hazardous cargo handling. Also, these operations are known to involve high-stakes decision-making, multi-variable monitoring as well as potential toxic exposure.

All such impacts are unfortunately largely overlooked in conventional fatigue scales. Additionally, no validated "HAZMAT Fatigue Index" exists to quantify the combined operational and cognitive burdens or loads on these crews. Psychosocial factors comprising vigilance stress, socia isolation, interpersonal conflict and job insecurity are all still treated as peripheral in fatigue risk models. While theoretical models such as JDCS and ERI acknowledge these dimensions, their integration with physiological and cognitive fatigue measures in maritime contexts is still quite minimal and by far marginal. Hence, maritime-specific adaptations of these models are urgently required. Comparably, sectors such as aviation, rail, and road transport have advanced fatigue research depending on the use of wearables, machine learning algorithms and real-time alertness monitoring. Besides, maritime research and operational practice are unfortunaly still lagging behind. Very few studies have traced biometric fatigue detection onboard, and no IMO or MLC provisions currently mandate real-time monitoring of cognitive readiness.

To bridge such gaps, the study at hand proposes a Multi-Layered Fatigue Risk Model for Hazardous Maritime Operations, Table 2. The recommended framework integrates operational, psychological, organizational, and technological dimensions into a unified system. Unlike traditional approaches, it stresses real-time data aggregation and adaptive feedback loops. Thus, the devised model can enable fatigue risk management to evolve dynamically in response to onboard conditions.

Table 2. Model Layers

Layer	Key Components	Examples
1. Operational	Duty cycles, shift length, cargo schedule	LNG bunkering schedule; tank cleaning duration
2. Psychological	Vigilance stress, decision fatigue, perceived risk	Readiness during emergency venting; self-assessed alertness
3. Organizational	Crew culture, leadership openness, manning adequacy	Permission to report fatigue; team rotation policies
4. Technological	Biometric sensors, alertness testing, smart logs	EEG headsets; wearable heart rate monitors; app-based diaries
5. Regulatory	Policy feedback, audit digitization, data-informed enforcement	Real-time fatigue audit; STCW/MLC updates

The recommended fatigue monitoring and management framework for hazardous cargo operations is conceived as a thorough, multi-tiered system grounded in Fatigue Risk Management System (FRMS) principles. What distinguishes this model, however, is its specific customization for maritime HAZMAT environments. The system begins by aggregating a wide array of input variables comprising:

- Biometric signals such as heart-rate variability and skin conductance.
- Cognitive function measures involving vigilance levels and response times.
- Operational factors such as duty rotations, task categories, and shift duration.
- Social and organizational indicators such as crew interaction quality and communication dynamics.

These datasets are then analyzed utilizing AI-enabled algorithms that assess fatigue likelihood and identify when individual or collective thresholds are at risk of being exceeded. Based on the analytical results, the system offers targeted, practical outputs in the form of:

- Automated notifications to designated safety personnel.
- Real-time modifications to work schedules or task allocations.

All generated monitoring data are afterwards recorded within the vessel's Safety Management System (SMS) and safely kept or stored on cloud platforms accessible to port-state regulators. This architecture incorporates transparency, accountability, and immediate operational responsiveness. It entirely meets international FRMS standards and also caters to the unique operational pressures associated with moving dangerous cargo. In light of the identified research gaps, future investigations are recommended to focus on the following critical dimensions and perspectives:

1. Development of HAZMAT-specific Fatigue Index integrating physiological, cognitive and operational markers.
2. Pilot studies with wearables on LNG and chemical tankers to test real-time fatigue monitoring as well as feedback loops.
3. Comparative fatigue database creation across vessel types, voyage lengths and operational roles.
4. Mixed-method research combining biometric monitoring, qualitative interviews and decision-tracking in simulated HAZMAT emergencies.
5. Policy simulation modeling to assess the effect of revised rest hours, crew rotations and biometric monitoring on long-term fatigue patterns.

8. Conclusion

Fatigue in hazardous maritime operations represents one of the most serious dangers posing a real threat to all parties engaged in this vital and intrinsic domain of maritime industry. Consequently, it is the responsibility of all those concerned with the safety of maritime sector to do their utmost in order to address such a crucial concern by all possible means. Considering the seriousnes of fatigue-related consequences on marine operations and dangerous cargo handling, the current research endeavor is basically meant to account for the relationship between crew fatigue, operational stress and safety in hazardous cargo transport and operations. Despite updated conventions, fatigue is still vasly a systematically underexamined risk with direct implications concerning health, safety as well as environmental protection. Based on the derived outcomes, fatigue is by no means merely a matter of long working hours, but the cumulative impact of operational, cognitive, organizational as well as cultural stressors. More importantly, current frameworks comprising STCW and MLC fall short of addressing real-world fatigue risks, specifically given issues such as falsified rest logs, poor or weak enforcement and stigma generally related to exhaustion. In light of the displayed case studies (e.g, Exxon Valdez, MSC Napoli), the combination of fatigue to poor safety culture could in most cases lead to catastrophic failures. Consequently, there is an urgent need for a comprehensive fatigue framework that integrates operational, psychological, organizational, and technological dimensions. From a practical perspective, fatigue mitigation can no longer rely on traditional checklist-style compliance solely. A transformative and truly effective solution necessitates a systemic overhaul of existing policies, incorporating proactive risk-management principles, advanced digital systems as well as wearable monitoring tools. The main aim is to achieve credible, permanent fatigue assessment while establishing supportive training and assistance structures that consolidate seafarers' well-being rather than penalize them.

In addition to that, the obtained results were compared to previous research, where areas of agreement as well as new contributions were consistently revealed. The derived outcomes corroborate earlier investigations that also identified workload, sleep deprivation, and environmental pressures as major determinants of seafarer fatigue. Nonetheless, the present analysis builds on earlier scholarship by emphasizing the combined impact of operational requirements and psychosocial stressors. It also stresses the distinguished role that cognitive fatigue represents in shaping performance levels and task effectiveness during hazardous cargo handling. Based on this integrated approach, the study provides a more practical understanding of fatigue risks. The comparative analysis at hand not only ascertains the validity of the current outcomes, but it also demonstrates the unique contribution of the current study to tackling crucial knowledge gaps in maritime fatigue investigation field.

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