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Maritime Trade at the Crossroads of Geopolitics

The maritime industry has always operated at the mercy of geography, but in today's world, geopolitics may be an even greater force than weather or tides. Few waterways illustrate this reality more clearly than the Strait of Hormuz, a narrow passage connecting the Arabian Gulf to global markets and carrying nearly a fifth of the world's oil supply each day. Whenever tensions rise in the region, the effects ripple far beyond the Middle East, reaching ports, shipping lanes, insurers, and consumers across the globe.

Recent escalations surrounding the Strait of Hormuz have once again exposed the vulnerability of international maritime trade to political instability. For shipowners and operators, the issue is no longer limited to delayed voyages or fluctuating fuel costs. It is a multidimensional challenge involving security risks, rising insurance premiums, rerouting decisions, crew safety, and mounting uncertainty in global supply chains. A single incident in this strategic corridor can trigger immediate reactions in freight markets and energy prices, reminding the industry how dependent modern commerce remains on safe and uninterrupted maritime passage.

The consequences extend beyond oil tankers alone. Container shipping, bulk carriers, offshore service vessels, and port operations all feel the pressure when geopolitical tensions intensify. Charter rates fluctuate, operational costs rise, and risk assessments become increasingly complex. Maritime insurers reassess war-risk zones, while shipping companies face difficult choices between commercial efficiency and operational security. At the same time, governments and naval coalitions strengthen their presence in critical sea lanes, further highlighting the strategic importance of maritime trade routes in global politics.

What makes the Strait of Hormuz particularly significant is not merely its geographic position, but its symbolic role in the interconnected global economy. In an era defined by just-in-time logistics and tightly linked supply chains, disruptions in one region can rapidly affect industries thousands of miles away. The maritime sector, often viewed as the invisible engine of globalization, is therefore becoming one of the first industries to absorb the shockwaves of geopolitical conflict.

Yet amid these challenges lies an important transformation. The industry is increasingly investing in resilience, through advanced risk management, diversified routing strategies, digital monitoring systems, and stronger international cooperation. Shipping companies are no longer preparing only for storms at sea, but also for volatility on the geopolitical horizon.

As tensions around the Strait of Hormuz continue to evolve, the maritime industry finds itself navigating more than commercial waters. It is steering through an era where geopolitics and shipping are inseparable, and where the stability of global trade may depend as much on diplomacy as on navigation itself.

Blockchain Digital Transformation: Enhancing Port Efficiency and Competitiveness in Egyptian Maritime Logistics

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المستخلص

تتناول هذه الدراسة الإمكانات المتقدمة لتقنية البلوك تشين في قطاع الموانئ المصري، مع التركيز على دورها في تعزيز الكفاءة الرقمية، ورفع مرونة العمليات، وترسيخ الثقة بين أصحاب المصلحة. ففي الوقت الذي أثبتت فيه موانئ عالمية مثل روتردام وسنغافورة وفالنسيا ولوس أنجلوس فعالية البلوك تشين في تبسيط سلاسل الإمداد البحرية، لا تزال الموانئ المصرية تواجه تحديات مرتبطة بالأنظمة التقليدية، وعدم وضوح الإطار التنظيمي، وضغوط التمويل، والمقاومة المؤسسية تجاه التحول الرقمي. ومن خلال دمج نتائج استبيانات أصحاب المصلحة مع تحليل دراسات حالة دولية، يقدّم البحث تقييماً شاملاً لمستوى النضج الرقمي في موانئ محورية مثل الإسكندرية، وبورسعيد، ودمياط، والسخنة، مع تحديد العوائق الحرجة والفرص الاستراتيجية لنشر حلول البلوك تشين.

تؤكد النتائج أن تبني البلوك تشين في الموانئ المصرية ليس خياراً تقنياً فحسب، بل ضرورة لتعزيز الأداء اللوجستي، وترسيخ ريادة إقليمية في تيسير التجارة الرقمية، واستثمار الموقع الاستراتيجي لقناة السويس. وتخلص الدراسة إلى أن البلوك تشين يجب أن يُنظر إليه كمنصة أساسية لبناء الثقة والشفافية والسيادة الرقمية في عمليات الموانئ، وليس مجرد أداة لرفع الكفاءة التشغيلية.

استناداً إلى هذه الرؤى، تقترح الدراسة خارطة طريق مرحلية قابلة للتنفيذ، تشمل إصلاحات قانونية، ووضع أطر معيارية للتشغيل البيني، وتوسيع مشاريع البلوك تشين التجريبية، وتعزيز الشراكات بين القطاعين العام والخاص، وبناء قدرات بشرية متخصصة. إن مواءمة تطبيقات البلوك تشين مع الاستراتيجية الوطنية للتحول الرقمي من شأنه تحويل المبادرات المتفرقة إلى منصة موحدة تُسهم في تطوير عمليات الموانئ، وجذب الاستثمارات، ودعم النمو المستدام في قطاع اللوجستيات البحرية المصري.

Abstract

This paper explores the potential of blockchain technology within the Egyptian port sector, emphasizing its role in enhancing digital capability, operational agility, and stakeholder trust. While global ports such as Rotterdam, Singapore, Valencia, and Los Angeles have demonstrated the effectiveness of blockchain in streamlining maritime logistics, Egyptian ports remain hindered by legacy systems, regulatory uncertainties, financial constraints, and institutional resistance. Through a combination of stakeholder surveys and analysis of international case studies, this research offers a comprehensive assessment of the digital maturity of key Egyptian ports such as Alexandria, Port Said, Damietta, and Sokhna, and identifies critical bottlenecks and strategic opportunities for blockchain deployment.

The findings affirm that blockchain adoption is not only feasible but essential for Egypt to enhance its logistics performance, assert regional leadership in digital trade facilitation, and leverage its strategic position along the Suez Canal. The study concludes that blockchain should be regarded not merely as an efficiency tool, but as a foundational enabler of trust, transparency, and digital sovereignty in port operations.

Based on these insights, Egypt can modernize its ports into 5th generation digital trade gateways, offering a scalable model for other nations in the Global South the paper proposes a phased, actionable roadmap emphasizing legal reform, standardized interoperability frameworks, pilot expansion, strengthened public private collaboration, and comprehensive capacity building. Aligning blockchain adoption with national digital strategy objectives can transform isolated pilots into a unified platform that improves port operations, attracts investment, and fosters sustainable growth in Egypt's maritime logistics sector.

Keywords: Blockchain, Maritime Logistics, Port Efficiency, Digital Transformation, NAFEZA, CargoX, Egypt.

1. Introduction

Ports serve as critical nodes in global trade networks, with their operational performance directly influencing a nation's competitiveness, trade costs, and supply chain resilience (Notteboom & Rodrigue, 2022, World Bank, 2022). In Egypt, the ports of Alexandria, Damietta, Port Said, East Port Said, and Ain Sokhna collectively handle a significant portion of national import and export activities (Ministry of Transport, Egypt, 2024). Their strategic location along the Suez Canal enhances their potential as both transshipment centers and gateway hubs linking Europe, Asia, and Africa (UNCTAD, 2023).

However, despite notable investments and modernization efforts, Egyptian ports continue to face procedural bottlenecks, repetitive documentation, and limited digital connectivity among key stakeholders (El-Dosouky et al., 2023, Soliman, 2025). Manual paperwork, overlapping inspections, and fragmented communication channels result in extended dwell times and increased transaction costs for shipping lines, freight forwarders, and authorities (World Economic Forum, 2023).

The digital transformation of ports extends beyond mere technological upgrades; it requires reshaping institutional structures, governance frameworks, and collaborative relationships across the logistics chain (Acciaro et al., 2021, OECD, 2024). Contemporary port systems depend heavily on integrated data flows to optimize berth management, shorten vessel turnaround, and ensure compliance with international standards (Port of Rotterdam Authority, 2021).

Within this evolving digital landscape, blockchain technology has emerged as a transformative enabler. Its decentralized ledger ensures an immutable, transparent, and auditable record of transactions accessible to authorized users reducing reliance on intermediaries and eliminating reconciliation delays (IBM & Maersk, 2022, Treiblmaier & van der Laan, 2021). In maritime logistics, blockchain enables secure trade document exchange, automated smart contract execution, and tamper-proof cargo and certificate tracking (World Bank, 2022, Notteboom & Winkelmans, 2023).

Egypt has already made preliminary progress in trade digitalization. The creation of the National Single Window (NAFEZA) has streamlined trade data submission, while the integration of CargoX represents an innovative application of blockchain in document exchange (Ministry of Finance, Egypt, 2023, CargoX, 2023). These milestones highlight the government's commitment to modernization, yet a single pilot project cannot deliver systemic reform. A gap remains between demonstrating blockchain's potential and achieving nationwide deployment across ports and related agencies (UNCTAD, 2023, Soliman, 2025).

This research therefore aims to assess Egypt's readiness and capability to expand blockchain adoption within the maritime logistics sector. The core objective is to identify technological, regulatory, organizational, and financial enablers and barriers to adoption, and to propose a practical implementation roadmap aligned with Egypt's national digital strategies (MCIT, 2024). The study employs a structured survey of maritime professionals and qualitative benchmarking against leading international cases to develop evidence-based recommendations that bridge the gap between pilot results and sector wide transformation.

2 Literature Review

This section reviews scholarly and practical literature on blockchain applications in logistics, focusing on transparency, traceability, smart contracts, and data security. It highlights the technology's transformative potential in improving efficiency, trust, and coordination among logistics stakeholders. The review also explores blockchain's technical foundations, adoption challenges, and its adaptability to maritime logistics, particularly in the Egyptian port context.

2.1 Blockchain and Port Digitalization

Ports are central nodes in global supply chains but often struggle with inefficiencies caused by fragmented communication systems, redundant documentation, and bureaucratic procedures.

These challenges result in higher costs, operational delays, and reduced competitiveness (Wang et al., 2021). Blockchain technology has emerged as a response to these inefficiencies, offering a decentralized and transparent method for recording and validating transactions. Its immutability ensures data integrity, while its peer-to-peer architecture enables trusted data exchange without intermediaries (Negi, 2022).

In port logistics, blockchain facilitates applications such as traceability, trade finance, and automation via smart contracts. For instance, blockchain enabled trade finance replaces manual verification with real-time authentication, reducing both costs and delays. However, despite successful applications in advanced economies, large scale implementation in developing regions including Egypt remains limited due to financial, regulatory, and infrastructural barriers (Othman et al., 2022).

2.2 Theoretical Foundations of Blockchain Technology

Blockchain functions as a distributed digital ledger that securely records transactions across decentralized nodes. Each transaction is grouped into a block, cryptographically linked to the previous one, creating an immutable and verifiable chain (Tsiulin et al., 2020). Key components include distributed ledgers, hash functions, consensus mechanisms, and smart contracts.

Distributed Ledgers: Ensure all participants access synchronized copies of records, minimizing reconciliation delays. Cryptographic Hashing: Prevents data tampering by creating unique digital fingerprints for each block. Consensus Mechanisms: Such as Proof of Work and Proof of Stake, validate transactions without central oversight, maintaining system trust (Wang et al., 2021).

Smart Contracts: Self-executing digital agreements automate port operations such as document verification and cargo release, reducing administrative costs (Alahmadi et al., 2022). The decentralized nature of blockchain enhances resilience by removing single points of failure and fostering secure data exchange among diverse actors' customs, port authorities, and shipping lines (Almeida, 2023). These attributes make blockchain particularly suitable for maritime logistics, where secure and transparent information flow is essential (Al-Masri, 2025).

2.3 Strategic Advantages of Blockchain in Maritime Logistics

Blockchain provides several strategic benefits to port operations and maritime logistics: transparency, efficiency, data integrity, and compliance.

1.Transparency and Trust: Blockchain's immutable ledgers foster shared visibility and accountability among stakeholders, reducing information asymmetry and reliance on intermediaries (Wang et al., 2021). This is especially valuable in Egypt, where traditional documentation systems often create delays and mistrust (Othman et al., 2022).

2.Operational Efficiency: Smart contracts automate repetitive tasks, accelerating cargo release and minimizing administrative errors. The CargoX–NAFEZA integration in Egypt exemplifies these benefits, reducing average cargo clearance times from 29 to 9 days (Othman et al., 2022).

Similarly, IBM-Maersk's TradeLens platform demonstrated 15–20% cost savings through paperless documentation (Wang et al., 2021).

3. Data Security: Blockchain's cryptographic structure ensures record integrity and protection against forgery or cyberattacks. In ports where sensitive trade documents are frequently exchanged, such security features mitigate fraud and unauthorized alteration (Alahmadi et al., 2022).

4. Regulatory Compliance: Time-stamped blockchain records streamline auditing and customs verification, enabling real-time compliance monitoring and faster clearance (Tsiulin et al., 2020). This reduces bureaucratic friction, one of the major obstacles in Egyptian port logistics.

5. Fraud Prevention and Risk Mitigation: Blockchain minimizes fraud by maintaining a tamper-proof and verifiable record of all activities (Almeida, 2023). As all participants share synchronized data, inconsistencies and manipulation become detectable, improving accountability.

6. Transaction and Payment Acceleration: Smart contracts automate settlements once conditions are met, eliminating manual banking processes and reducing transaction delays (Ababneh et al., 2023). This efficiency is critical in international trade, where delayed payments often incur demurrage and liquidity constraints.

7. Scalability and Integration: Blockchain systems can integrate with emerging technologies such as IoT and AI for real-time cargo tracking and predictive analytics (Wang et al., 2021). Such convergence enhances supply chain visibility and supports Egypt's ambition to become a regional logistics hub at the crossroads of three continents.

2.4 Applications in Port and Supply Chain Logistics

Blockchain addresses long-standing challenges in global logistics, especially in data fragmentation, document fraud, and limited traceability. Its applications in port logistics include:

1.End-to-End Traceability: Real time cargo tracking ensures transparency and reduces theft and loss (Wang et al., 2021).

2. Smart Contracts: Automate customs release and payment validation, improving throughput efficiency (Tsiulin et al., 2020).

3. Trade Documentation: Digital bills of lading and certificates of origin increase speed and accuracy in documentation (Othman et al., 2022).

4. Regulatory Integration: Customs authorities can directly verify documentation on blockchain, reducing manual inspections and corruption opportunities.

5. Cold Chain Monitoring: Combining blockchain and IoT ensures that perishable goods maintain quality standards throughout the logistics chain (Ahmet Yunus Cil et al., 2022).

2.4 Case Studies of Blockchain in Port Operations

Global experiences underscore blockchain's role in improving logistics efficiency and stakeholder collaboration.

1. Port of Rotterdam: Introduced blockchain-based data exchange (Deliver Project), improving vessel turnaround by 20% through real time coordination among customs, shipping, and terminal operators (Tsiulin et al., 2020).

2. Port of Valencia: The EU's Data Ports initiative digitized VGM certificates, reducing processing time by 30% while ensuring SOLAS compliance (Almeida, 2023).

3. Port of Los Angeles: Integrated blockchain within its Port Optimizer™ to enhance cybersecurity and visibility across its logistics chain (Port of Los Angeles, 2019).

4. **Port of Singapore**: The SGTraDex platform connects port authorities, financial institutions, and logistics firms, integrating blockchain with IoT and AI for end-to-end trade visibility (IMDA, 2022).

5. TradeLens (IBM-Maersk): A global blockchain network connecting over 300 entities, improving data transparency, and automating documentation across 600 ports (Ababneh et al., 2023).

These initiatives collectively demonstrate how blockchain fosters transparency, compliance, and process automation, while also highlighting scalability challenges relevant to Egypt's modernization journey.

2.5 Adaptability to Egyptian Ports

Egypt's ports Alexandria, Damietta, Port Said, and Ain Sokhna handle nearly 90% of national trade (Othman et al., 2022). Yet, reliance on manual documentation and legacy IT systems limits their competitiveness. Integrating blockchain within Egypt's existing digital platforms, such as NAFEZA, offers a foundation for modernization. However, effective implementation requires regulatory reform, infrastructure upgrades, and capacity building.

Drawing from the experiences of Rotterdam, Valencia, Singapore, and Los Angeles, Egypt can adopt a phased strategy beginning with customs digitalization and scaling toward full port community integration. Such progress aligns with Egypt Vision 2030 and the transition from traditional to fifth generation smart ports (UNCTAD, 2024).

2.5.1 Evolution of Seaport Generations

UNCTAD's framework traces seaport development through five successive generations, each defined by growing complexity, integration, and technological capability (UNCTAD, 1991, 2017).

First generation ports: were largely functional facilities focused on basic loading, unloading, and storage operations. Operating in noncompetitive environments, they primarily handled bulk and raw materials. Although technologically simple, such ports were crucial to regional economic activity in developing nations.

Second-generation ports: (1960-1980) emerged with the industrialization era, linking maritime operations to nearby industries and trade zones. They expanded cargo types especially bulk and liquid commodities and improved infrastructure and hinterland connectivity. However, operations remained largely manual, with limited information exchange or environmental regulation (UNCTAD, 1991).

Third-generation ports: (post-1980) reflected the impact of globalization and containerization. They evolved into logistics hubs with broader roles in storage, documentation, and integrated distribution. These ports began using computerized systems for cargo tracking and operational planning, marking the early stages of digitalization and international supply-chain connectivity (Tsiulin et al., 2020).

Fourth-generation ports: (1990s onward) were conceived as global trade facilitators supported by public private partnerships. Their strategies extended beyond infrastructure to include regulatory compliance, workforce development, and stakeholder coordination. Scholars such as Beresford have criticized this generation for lacking standard classification criteria, emphasizing instead the importance of human capital, environmental awareness, and innovation culture in port competitiveness (UNCTAD, 2017).

Fifth-generation ports: represent today's most advanced stage, operating as smart, interconnected logistics ecosystems. They employ automation, artificial intelligence, and blockchain to achieve real-time transparency and predictive decision-making. These ports integrate maritime and inland logistics, focus on sustainability, and provide value-added services exceeding regulatory standards (Kaliszewski, 2018). Fifth-generation facilities thus serve as innovation clusters—actively engaging stakeholders and driving digital trade growth.

2.5.2 Technical and Infrastructure Readiness

Effective blockchain deployment in ports depends on advanced ICT infrastructure, interoperability, and data standardization. While Egypt has launched initiatives such as the NAFEZA single window system, many terminals still rely on paper-based workflows (Othman et al., 2022).

Digitization of customs processes, manifests, and vessel scheduling is essential to ensure that blockchain data inputs are accurate. Connectivity between Port Community Systems (PCS), customs, and terminal operators remains uneven across Egypt's ports. Facilities such as Ain Sokhna, managed by DP World, are more digitally mature, whereas others require upgrades in automation and integration (Almeida, 2023).

Modern ports increasingly use Automated Stacking Cranes (ASCs) to improve yard efficiency and safety. ASCs allow higher-density container storage, consistent handling, and integration with

Terminal Operating Systems for real-time visibility. Despite their benefits in speed and energy efficiency, ASCs involve high initial investment and maintenance complexity. Therefore, a phased adoption approach beginning with technologically advanced terminals is the most feasible path for Egypt’s blockchain transition.

2.5.3 Organizational and Stakeholder Readiness

Blockchain’s success depends as much on institutional cooperation as on technology. Egypt’s port ecosystem involves multiple stakeholders’ customs, port authorities, terminal operators, and freight forwarders often operating in silos. Building trust and shared governance is thus critical (Wang et al., 2021).

Pilot programs like CargoX & NAFEZA have demonstrated blockchain’s benefits in reducing clearance times and enhancing transparency (Othman et al., 2022). Expanding such pilots to include banks, insurers, and logistics firms can strengthen stakeholder confidence and encourage broader adoption.

2.5.4 Regulatory and Policy Alignment

A robust regulatory framework is vital for blockchain implementation. Current Egyptian trade laws do not yet recognize smart contracts or electronic bills of lading as legally binding, limiting institutional confidence (Ababneh et al., 2023). Issues of data privacy, jurisdiction, and international interoperability also require legal clarity. Comparative experiences from Rotterdam and TradeLens* show that regulatory sandboxes controlled environments for innovation can accelerate blockchain adoption (Tsiulin et al., 2020). Establishing such mechanisms within Egypt’s Customs Authority would allow gradual legal adaptation while ensuring compliance and security.

2.5.5 Process Integration and Incremental Implementation

Blockchain’s modular architecture enables step by step integration without full system replacement. Egypt could follow models like the Port of Valencia, which digitized weight certification (VGM) through a targeted blockchain pilot (Ababneh et al., 2023).

Initial Egyptian pilots could focus on customs pre-clearance, inter-terminal transfers, or cargo release to generate “quick wins” and demonstrate value to stakeholders. Building on CargoX success, these processes can later link with legacy systems through standardized APIs for smoother interoperability (Othman et al., 2022).

2.5.6 Economic Rationale and Development Impact

Blockchain’s ability to streamline logistics, reduce transaction costs, and attract investment strengthens its economic justification. Transaction cost economics suggests that reducing monitoring and enforcement costs promotes efficiency and competitiveness (Tsiulin et al., 2020).

In Egypt, blockchain adoption could improve logistics performance, enhance Suez Canal trade flows, and generate new value-added services such as secure document storage and digital certification. Specific ports could leverage blockchain in tailored ways:

- Alexandria: automate customs clearance.

- Port Said: improve container tracking.
- Damietta: support trade finance for bulk commodities.

These applications would support Egypt’s Vision 2030 goals and position its ports as digital trade leaders in the MENA region.

2.6 Research Gaps

Existing literature on blockchain in maritime logistics offers global perspectives but limited empirical focus on Egypt. Studies like Othman et al. (2022) and Wang et al. (2021) highlight digitalization challenges broadly but lack country-specific analysis of blockchain readiness. Comparative works (Tsiulin et al., 2020; Almeida, 2023) often generalize developing economies, overlooking Egypt’s regulatory and infrastructural nuances.

No comprehensive research has yet combined stakeholder surveys with case studies of Egyptian ports to assess blockchain adoption barriers and opportunities. Gaps remain in understanding:
- Stakeholder perceptions and readiness for blockchain integration.
- Technical and infrastructural capacities across major ports.
- Legal and cultural challenges, including resistance to automation.

Addressing these gaps will guide policymakers and industry leaders in designing actionable strategies for blockchain deployment in Egyptian ports advancing national competitiveness and regional digital transformation.

3. Methodology

The study uses a mixed method approach combining quantitative and qualitative tools. A structured questionnaire was distributed among **130** maritime professionals from port authorities, customs, terminal operators, shipping agents, and freight forwarders. **112** valid responses were received (86% response rate). Sampling followed the stratified method to ensure coverage of public and private ports.

A quantitative, deductive approach was used to test hypotheses concerning blockchain readiness and its relationship with port efficiency. Data were gathered through a self-administered questionnaire distributed among logistics, customs, and IT professionals. Descriptive and regression analyses were conducted using SPSS to identify statistically significant relationships among variables.

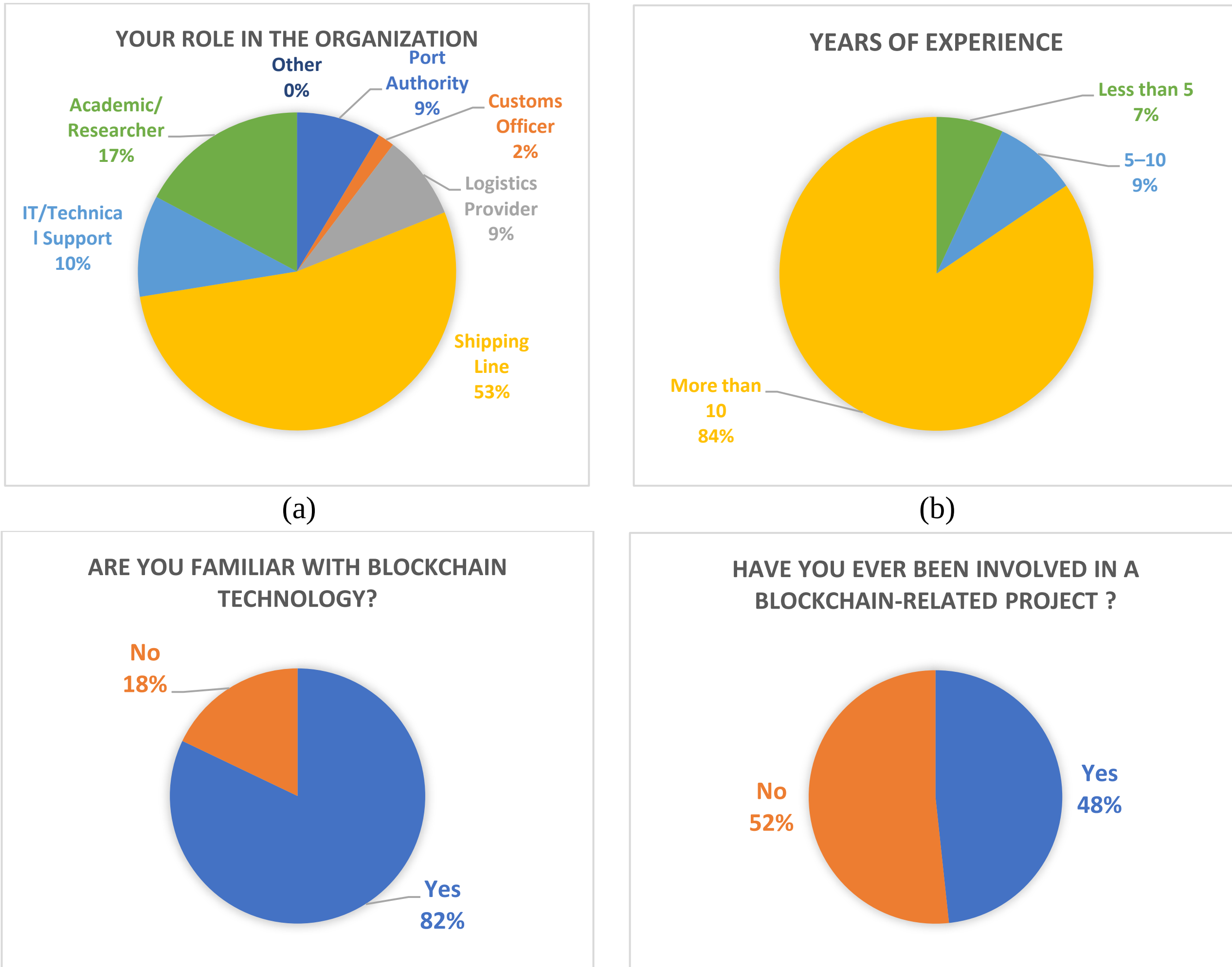

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Figure (1): Respondent Profile by Sector, Experience, and Blockchain Involvement.

3.1 Key Findings

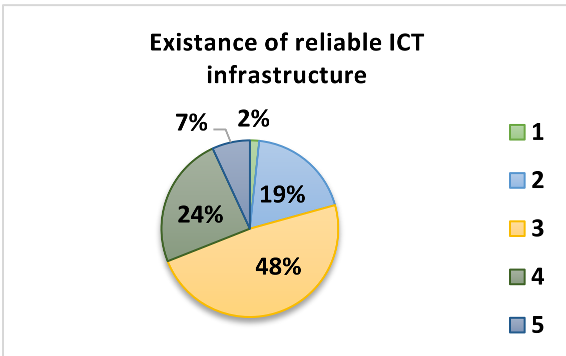
1. Technological Readiness: Most respondents (≈69%) agreed that current ICT infrastructure is insufficient to support blockchain. Weak API integration, outdated terminal systems, and limited in house technical expertise were cited as major constraints (Tsiulin et al., 2020). While ports like Sokhna show digital maturity, others remain largely manual, restricting interoperability.

2. Financial Constraints: Around 75% of respondents viewed blockchain implementation as cost prohibitive. Limited public funding and the absence of clear ROI models slow adoption. Unlike EU backed projects in Rotterdam, Egyptian ports rely primarily on national budgets (Alahmadi et al., 2022). Public private partnerships and external financing were identified as potential enablers.

3. Regulatory Environment: Only 24% believed Egypt's legal framework sufficiently supports blockchain. The absence of laws recognizing smart contracts or digital records deters investment

(Othman et al., 2022). Respondents emphasized the need for data governance, privacy regulation, and standardized digital trade policies.

4. Stakeholder Readiness: Approximately 77% highlighted limited blockchain awareness among mid-level managers. Concerns over job displacement, low digital literacy, and cultural resistance persist (Wang et al., 2021). Trust gaps between public and private entities further hinder cooperation.



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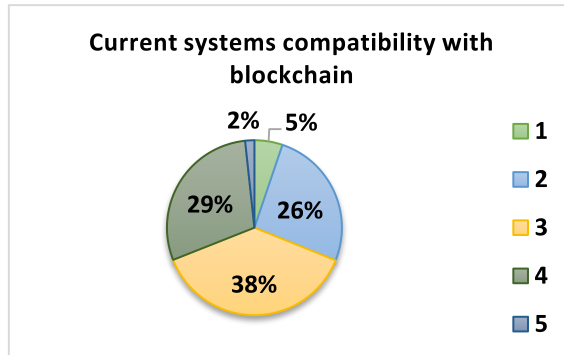

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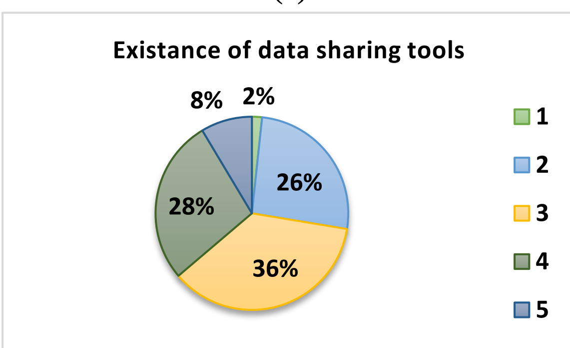

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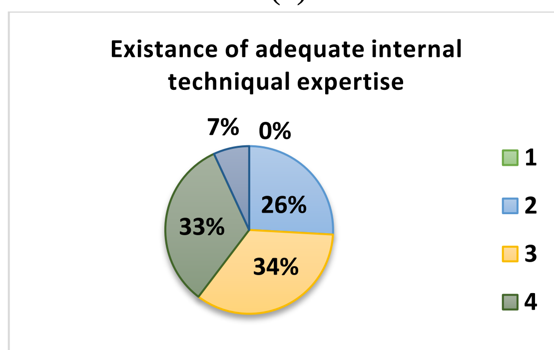

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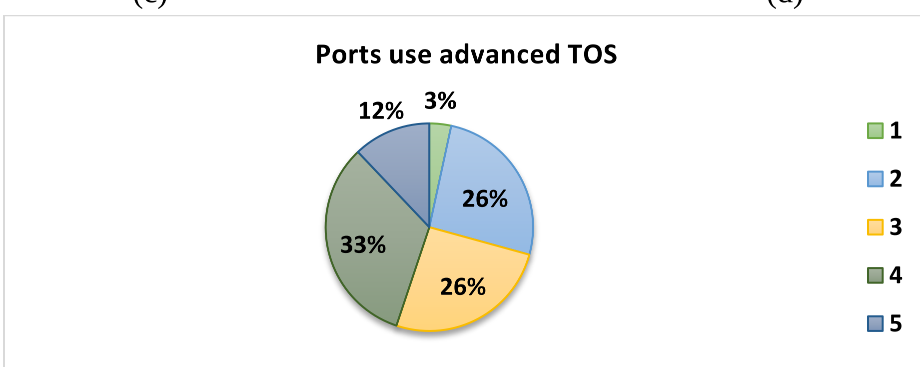

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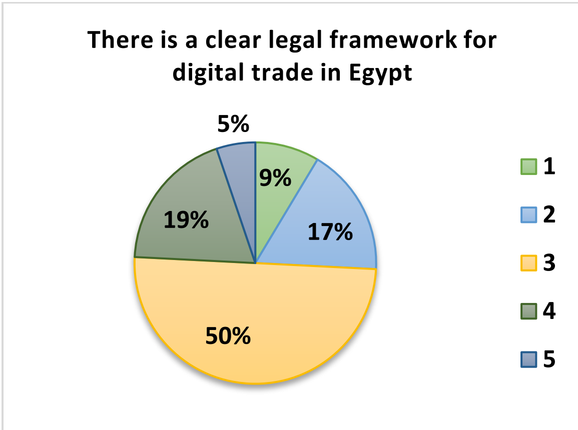
Figure (2): Technological Readiness Indicators in Egyptian Ports values represent the percentage of respondents agreeing with each statement regarding ICT infrastructure, system integration, and tech expertise.



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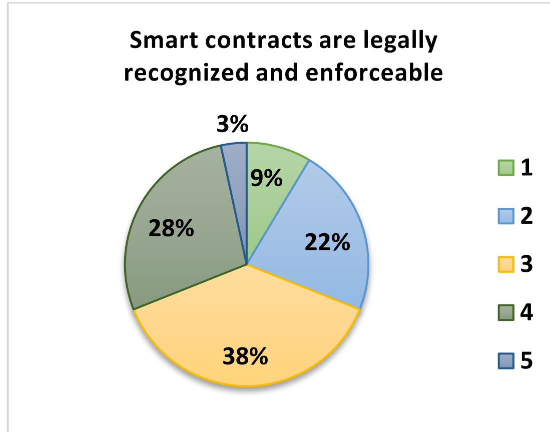

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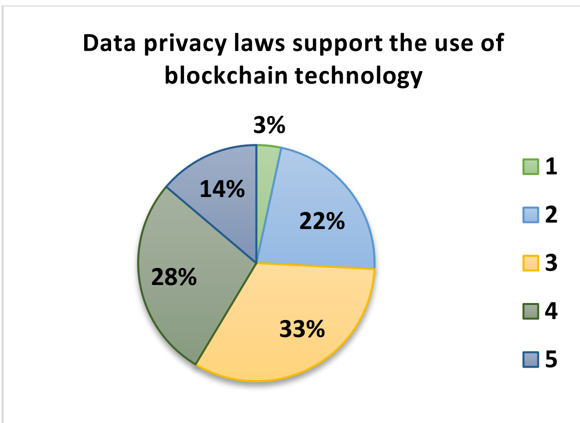

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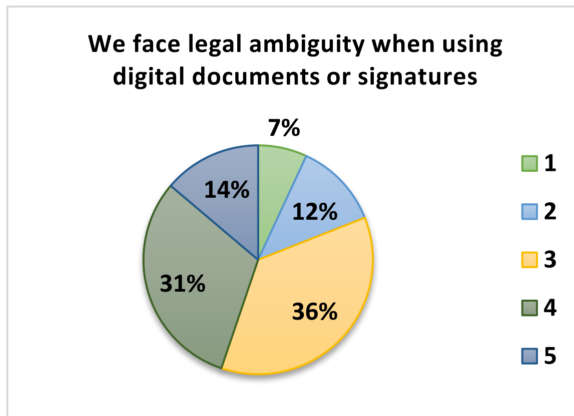

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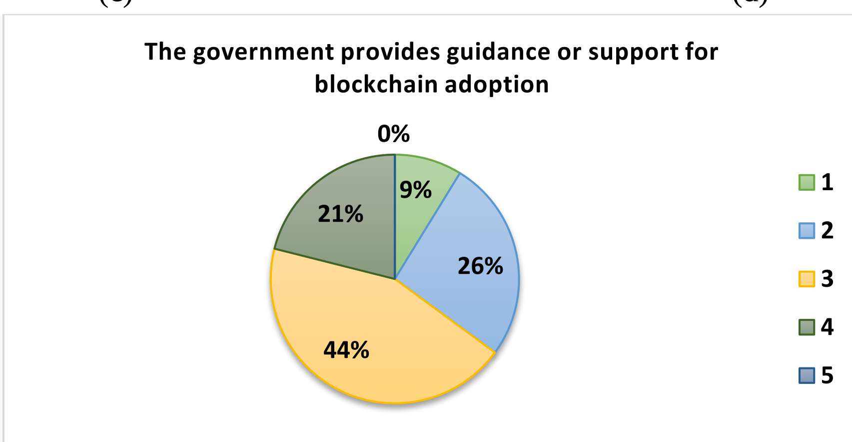

(e)

Figure (3): Perceptions of the Regulatory Environment for Blockchain Adoption
Values represent the percentage of respondents agreeing with statements about legal frameworks, smart contracts, and government support.

3.4 Hypothesis Testing

This research treats the 112 survey respondents as a representative sample of the broader population of professionals engaged in Egyptian port operations, customs, logistics, and IT. The objective is to test whether technological readiness and blockchain enabled transparency significantly influence port efficiency and competitiveness across the entire professional population.

Two hypotheses were tested using regression analysis:

- **H_1:** Technological readiness significantly improves port efficiency and competitiveness.
- **H_2:** Blockchain enabled transparency and data security significantly enhance port efficiency and competitiveness.

The results of Hypothesis testing can be summarized as follows:

- **H_{A1}:** (Accepted, $p = 0.00004$, $R^2 = 0.25$)- Technological readiness explains ~25.7% of the variance in port efficiency.
- **H_{A2}:** Accepted ($p = 0.00094$, $R^2 = 0.179$) – Blockchain enabled transparency explains ~17.9% of the variance in port efficiency.

Results confirm that both technological readiness and blockchain enabled transparency to have statistically significant positive impacts, though technological readiness explains a larger share of variance in port efficiency.

Table (1): Hypothesis Test

Model	R-squared	P-value	Coefficient
Technological Readiness	0.256802655	0.00004914	0.520763211
Blockchain Transparency	0.178868112	0.00094134	1.859765272

Statistical analysis of hypothesis testing.
N = 112. All p-values are < 0.05, indicating statistical significance.

3.5 Stakeholder Support (NPS Analysis)

To complement the regression analysis, the Net Promoter Score (NPS) was calculated to evaluate stakeholder perceptions toward blockchain adoption in Egyptian port operations. Respondents were asked:

On a scale from 0 to 10, how likely are you to recommend the adoption of blockchain in Egyptian port operations?

Responses were classified into three categories:

- **Promoters (9–10):** Strong advocates who are highly likely to recommend blockchain adoption.
- **Passives (7–8):** Neutral or moderately supportive, but not strong advocates.
- **Detractors (0–6):** Opposed, unlikely to recommend adoption.

The NPS is calculated based on stakeholder responses to a 0–10 rating scale. Respondents scoring 9–10 are classified as Promoters (strong advocates), those scoring 7–8 are Passives (neutral or moderately supportive), and those scoring 0–6 are Detractors (unlikely to recommend). The NPS is determined by subtracting the percentage of Detractors from the percentage of Promoters. This produces a score ranging from –100 (all respondents are Detractors) to +100 (all respondents are Promoters). Higher values indicate stronger overall support for blockchain integration, while negative scores reflect more opposition than advocacy.

The Net Promoter Score (NPS) measured overall sentiment toward blockchain. In this research, Promoters accounted for **53.6%** of respondents, Passives for **26.8%**, and Detractors for **19.6%.** Applying the NPS formula:

$$\mathbf{NPS = \%Promoters - \%Detractors = 53.6 - 19.6 = +34}$$

An NPS of **+34** This positive score indicates that a significant proportion of the professional population is supportive of adopting these innovations aligning with the study's hypotheses that both technological readiness and blockchain-enabled transparency positively influence port efficiency and competitiveness.

The chart below showcases the distribution of respondents into Promoters, Passives, and Detractors based on their chances of recommending progressive technological solutions and blockchain-enabled transparency in the Egyptian port operations.

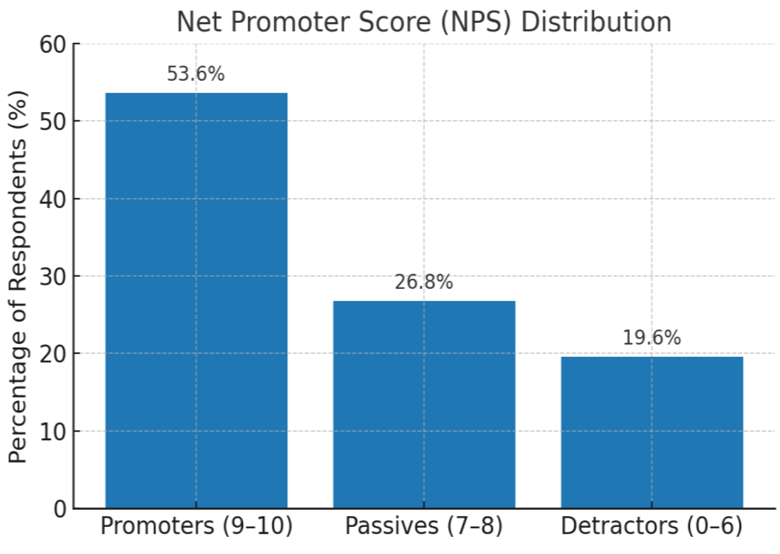

Figure (4): Net \promoter Score distribution.

4. Findings & Discussion

The research confirms that blockchain adoption challenges in Egypt's maritime logistics sector are multifaceted spanning technology, finance, regulation, and stakeholder engagement. Unlike advanced European ports supported by strong digital ecosystems and clear legal frameworks, Egyptian ports still operate through fragmented systems with limited interoperability and constrained budgets. These weaknesses restrict the scalability of blockchain initiatives.

4.1 Awareness and Strategic Perception

Survey data indicates broad conceptual awareness of blockchain's potential to reduce paperwork, enhance traceability, and strengthen trust among trading partners (Kouhizadeh et al., 2021). Senior management and IT specialists show the highest levels of strategic understanding, while frontline staff though not resistant display limited knowledge of blockchain's operational mechanisms. Interviews reveal ongoing confusion between blockchain and other digital systems, with some respondents still associating it primarily with cryptocurrency (Saberi et al., 2019). This indicates an early adoption stage where general awareness exists, but deep technical and procedural expertise remains underdeveloped.

4.2 Technological Readiness

Findings suggest moderate technological preparedness. Privately managed terminals and concessioned facilities, motivated by commercial efficiency and flexible governance, exhibit stronger system integration and more modern digital infrastructure (World Bank, 2023). Conversely, publicly managed ports continue to rely on legacy platforms with minimal interoperability. Few organizations have initiated blockchain-related pilot programs or established architectural frameworks to link with distributed ledger solutions. Key deficiencies include incompatible data standards, limited API access from older systems, and uneven cybersecurity capabilities all of which impede seamless, secure data exchange across the port ecosystem (UNCTAD, 2022).

4.3 Regulatory Environment

Regulatory clarity stands out as a critical factor. Respondents consistently identified the lack of formal legal recognition for blockchain based trade documentation, particularly electronic bills of lading and smart contracts, as a primary impediment (OECD, 2021). Although the national single window platform centralizes data submission, it does not yet confer full legal status to blockchain-generated records. Interviewees emphasized the urgency of introducing legislative reforms or policy guidelines that establish blockchain outputs as legally valid and enforceable (WTO, 2023). Without such recognition, banks, insurers, and judicial bodies remain cautious about transacting exclusively through distributed ledgers.

4.4 Financial and Investment Considerations

Financial constraints represent a pragmatic challenge. Implementation requires funding for infrastructure modernization, system integration, cybersecurity reinforcement, and employee training (Rodrigues et al., 2021). For many public entities operating with limited budgets, these costs are significant without external financing or cost-sharing partnerships. While private operators are more financially capable, they demand clear return-on-investment projections through measurable reductions in turnaround times, dispute resolution costs, and administrative inefficiencies. Interviews underscored that collaborative funding mechanisms, including public private partnerships and targeted incentives, could substantially boost adoption rates (World Economic Forum, 2022).

4.5 Organizational Readiness and Human Capital

Organizational readiness reveals mixed progress. Leadership endorsement exists at upper management levels, but operational execution remains weak. A recurring issue is the absence of structured training programs focused on blockchain and digital logistics (Notteboom & Haralambides, 2020). Interviewees proposed modular training, professional certification pathways, and collaboration with maritime academies to cultivate skilled personnel. Addressing cultural resistance to automation requires a structured change management approach emphasizing stakeholder inclusion, transparent communication on job transitions, and upskilling initiatives that position digitalization as a complement rather than a threat to human roles (Hildebrandt et al., 2022).

4.6 Evidence from Pilot Integration: CargoX and the Single Window

The integration of CargoX within Egypt’s national single window platform demonstrates blockchain’s practical value in improving documentation efficiency and traceability (CargoX, 2024). Recorded reductions in document handling and customs clearance times highlight measurable productivity gains achieved through digital workflows (Egypt Ministry of Finance, 2023). However, the pilot remains limited in scope, it focuses primarily on document exchange and does not yet interface with terminal systems or inland logistics networks. Consequently, while promising, it represents only an initial milestone toward a fully interconnected, end-to-end blockchain ecosystem incorporating IoT and cloud based technologies (UNCTAD, 2023).

4.7 Comparative Lessons from International Examples

Global benchmarking provides several actionable lessons. Successful international implementations are typically driven by coherent policy frameworks and coordinated institutional efforts rather than technology alone (Port of Rotterdam, 2022; Maersk & IBM, 2021). Governments that established clear regulations and interoperable data standards achieved faster adoption. Equally vital is the standardization of APIs and data formats to prevent vendor dependency and ensure platform flexibility (IMO, 2023). Progressive scaling through focused pilot projects covering document exchange, customs pre arrival processing, or secure certification helps demonstrate tangible key performance indicators (KPIs) that justify expansion. Furthermore, joint investment models and public private partnerships accelerate infrastructure readiness and foster market competitiveness (World Bank, 2023).

4.8 Integrated Interpretation

Overall, the empirical evidence places Egypt at a strategic turning point. Initial pilot projects have confirmed blockchain's potential, leadership awareness is growing, and private operators have demonstrated commercial feasibility. The key remaining challenges are institutional and financial rather than technological. Overcoming them will require a coordinated national framework combining legal reforms, targeted funding mechanisms, pilot expansion, and human capacity development. A multi layered strategy integrating regulation, finance, technology, and training can transform early pilot efforts into a sustainable, interoperable digital ecosystem that enhances the efficiency and competitiveness of Egyptian maritime logistics.

5. Research Limitations and Future Directions

This research focused on major Egyptian seaports, smaller inland logistics operators were underrepresented. Future studies should use longitudinal data to track evolving digital transformation and employ simulation models (e.g., system dynamics) to estimate cost benefit impacts.

While this research provides valuable insights into the potential of blockchain for enhancing the efficiency and competitiveness of Egyptian ports, several limitations should be acknowledged.

First, the analysis relied primarily on self-reported survey data, which may involve perceptual biases or subjective optimism among respondents. Future research could incorporate objective performance indicators, such as port turnaround time, cost reduction metrics, or blockchain transaction efficiency, to validate the perceived outcomes.

Second, the study adopted a cross sectional design, capturing stakeholder perceptions at a single point in time. Given the rapidly evolving nature of digital transformation, longitudinal studies would help track how adoption readiness and institutional attitudes change over time as new technologies mature.

Third, although the survey covered major Egyptian ports, smaller inland logistics operators and private terminal entities were underrepresented, potentially limiting generalizability. Expanding the sampling frame to include more diverse logistics actors could enrich the understanding of blockchain diffusion across the wider maritime ecosystem.

Finally, while the research applied a mixed method approach, it did not employ quantitative simulation or econometric modeling to estimate cost benefit impacts. Future studies could integrate data driven modeling, system dynamics, or digital twin simulations to measure the economic and operational gains of blockchain adoption at scale.

Acknowledging these limitations provides a foundation for future research to build upon, ensuring that Egypt's blockchain transformation in maritime logistics evolves through continuous empirical refinement and multidisciplinary collaboration.

6. Conclusion

Blockchain represents a practical and transformative tool for enhancing document integrity, automating conditional workflows, and fostering transparency across maritime logistics chains. Within Egypt, early pilot projects have demonstrated clear operational benefits while simultaneously revealing the need for deeper institutional alignment and policy coordination. The critical enablers of successful adoption extend beyond technology they rest on governance foundations that include legal recognition, interoperability standards, inter agency collaboration, and workforce competency. Focusing solely on technical deployment without concurrent regulatory reform and capacity development will constrain results, likewise, policy changes unsupported by technological infrastructure will fail to yield measurable improvements. Therefore, blockchain implementation must be pursued as an integrated component of Egypt's national digital transformation strategy, positioned not merely as a technological upgrade but as a systemic and institutional innovation.

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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.

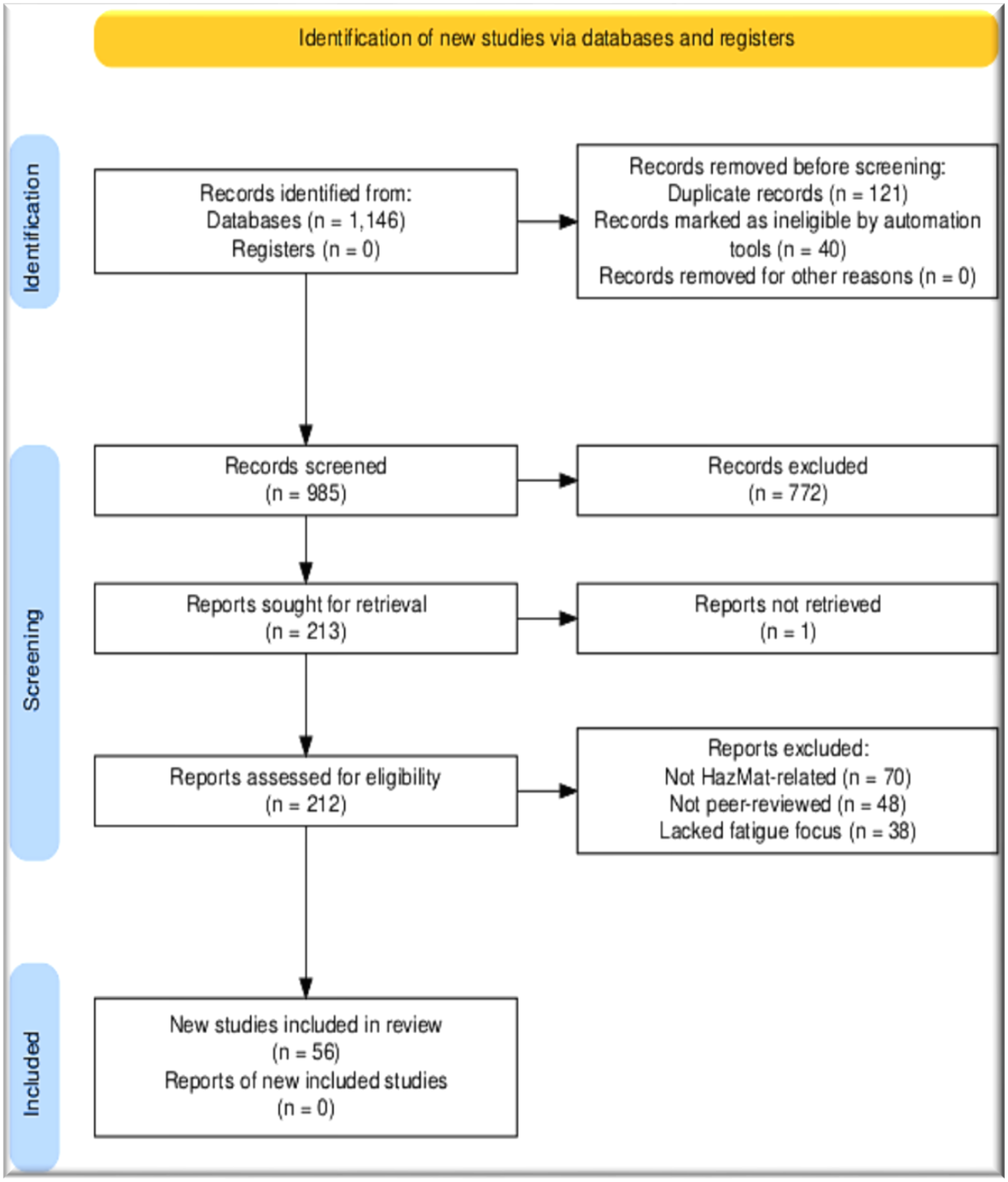

Figure 1. PRISMA 2020 flow diagram of study selection and screening process.

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.

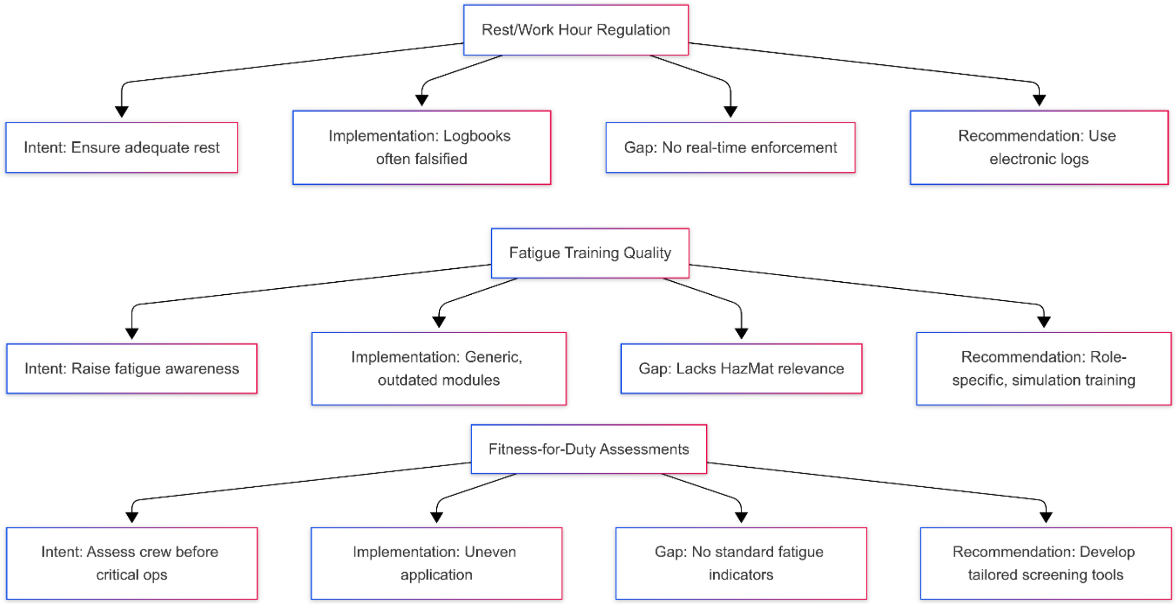

Figure 2. Matrix-based regulatory gap analysis of STCW 2010 and MLC 2006 provisions related to fatigue

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.

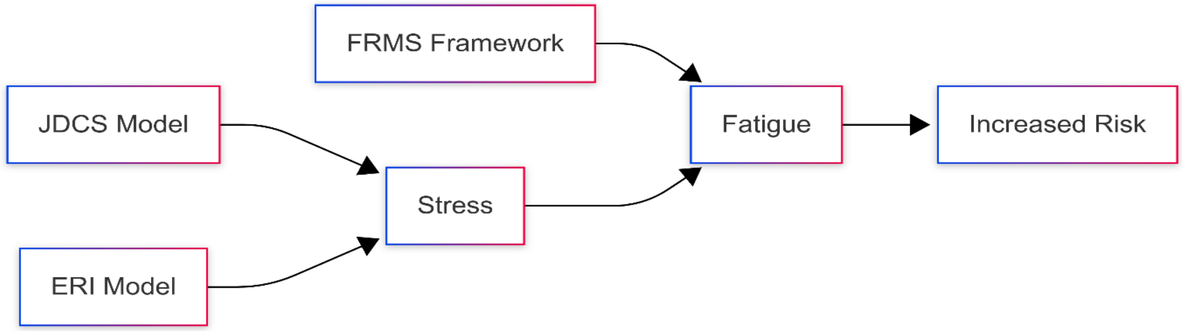

Figure 3. Conceptual chain from stress to fatigue to risk, integrating JDCS, ERI, and FRMS elements within hazardous maritime operations.

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).

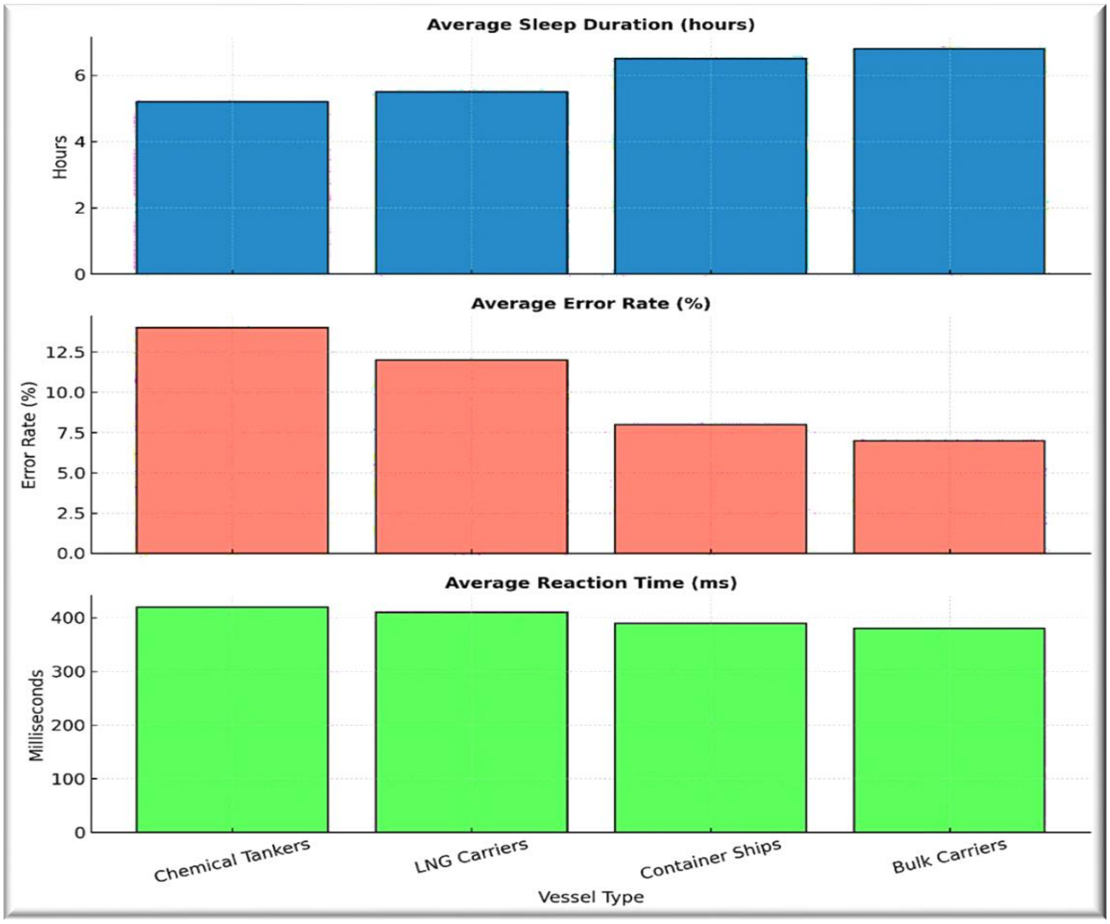

Figure 4. Comparative fatigue indicators across vessel types.

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.

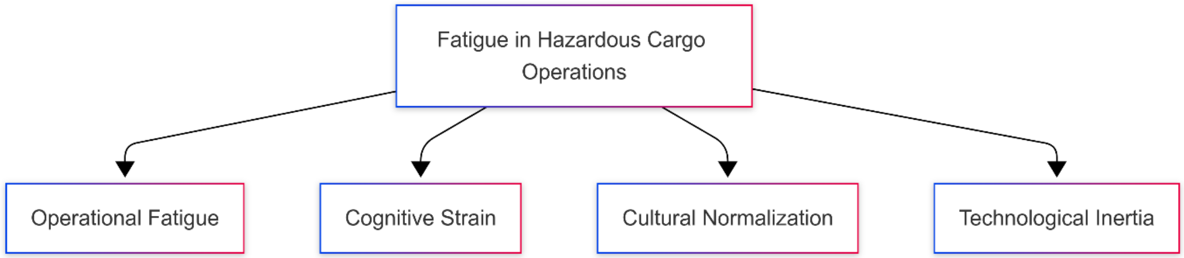

Figure 5. Thematic analysis of fatigue in hazardous cargo operations

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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An integrated analysis of key factors causing fires in high-tier containers on Ultra-Large Container Vessels

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المستخلص

يهدف هذا البحث إلى تحديد العوامل المنطقية الكامنة وراء العامل البشري، ونقص التصريح عن البضائع الخطرة، وغياب نظام متطور للكشف عن الحرائق، وهي الأسباب الرئيسية لاندلاع الحرائق في الحاويات المخزنة في الطبقات العليا على سفن الحاويات العملاقة، بالإضافة إلى استكشاف الحلول المحتملة مثل الوقاية من الحرائق والتخفيف من حدتها؛ وقد استخدم الباحث الأساليب الوصفية التحليلية وطوّر استبيانًا وُزّع على البحارة، حيث تأهلت ١٥٦ استجابة للمعالجة باستخدام برنامج SPSS الإصدار v٢٦، وقد أبرزت النتائج أن أكثر العوامل تأثيرًا كانت العوامل البشرية، والبنية التحتية للكشف عن الحرائق، وعدم الإعلان البضائع الخطرة ، وبناءً عليه، يوصي البحث بضرورة توفير أنظمة أكثر تطوراً للوقاية من الحرائق، وتنفيذ لوائح وقوانين أكثر صرامة بشأن البضائع المعرضة لخطر الحريق، وتطبيق تدريب للتخفيف من مخاطر الحريق على طاقم السفينة، ويُعمم هذا العمل لمشغلي السفن والجهات التنظيمية وأصحاب المصلحة في قطاع النقل البحري لتعزيز ممارسات السلامة وحماية الأرواح والبضائع والبيئة البحرية.

Abstract

The purpose of this research is to determine the reasoning behind the human factor, the lack of declaration of dangerous goods, the lack of a sophisticated fire detection system, the primary causes of fire outbreaks on high-tier stowed containers on Ultra Large container vessels (ULCVs), and potential answers: fire prevention and fire mitigation. The researcher employed descriptive-analytical techniques and developed a survey distributed to seafarers. 156 responses qualified. They were processed using SPSS v26. The researcher brought to light the most impactful of which were human factors, fire detecting infrastructure, and lack of declared dangerous cargo. It is recommended in this research that more sophisticated fire prevention systems should be in place, more stringent regulations on fire-hazardous cargo should be implemented, and that fire risk mitigation training should be implemented on the part of the crew. This research is disseminated to ship operators, the fire safety practices regulatory and stakeholders in the maritime transport sector to enhance fire safety practices and protect life, cargo, and the marine environment.

Keywords: Ultra Large Container Vessels (ULCVs) – Container Fire Safety - Human Error - Undeclared Dangerous Goods - Fire Detection Technology - Marine Accidents

1. Introduction

Maritime transport is the backbone of trade and the core of the global economy by contributing to the transfer of intercontinental trade, as it represents the transportation of raw materials, foodstuffs, and manufactured goods, with more than 80% of the products being transported around the world, and 70% of the global trade value is transported by ships of all types (Salihoglu and Beşikçi, 2021). Around 60 thousand merchant vessels of various types and sizes are roaming the world to transport all kinds of goods (Deggim, 2021). Due to the industry's sheer scale and its vital role in supporting international commerce, considerable attention has been directed by global maritime bodies toward the challenges it encounters. In particular, the issues of safety of navigation and protection of the marine environment drew the attention of scholars and led to the continued development of global regulations and international cooperation at different levels (Helal, 2021).

There have been changes in the design and size of container ships within the last 10 years. The larger the ships get and the more cargo they can hold, the greater the concentration of boxes on a limited number of vessels. This concentration increases the likelihood of container fires and explosions, resulting in catastrophic losses (Krmek et al, 2022). The safety of the entire marine transport system is jeopardized due to fires on vessels, as assets, cargo, and lives can be lost, and there is pollution of the ecosystem (Luo and Shin, 2019). The losses, especially the ones that stem from ship fires, are devastating in many aspects, including the safety of the crew, the ecosystem, and the financial and social image losses for the shipping line (Avazov et al, 2023).

As noted in the Safety and Shipping Review (2023), fires were the second leading cause of complete loss of a vessel for the year prior, contributing to 18% of the total value of the analyzed insurance claims.

The last decade has seen a reduction in total losses of shipping because of advances in technology and better training of crews. However, fires have not seen a corresponding reduction. The year 2022 recorded 209 incidents of fire, the highest in the last 10 years. One such fire was in January of 2022, when a vessel carrying over four thousand luxury brands, such as Porsche, Audi, Bentley, and Lamborghini, caught fire in the Mid-Atlantic, and two firefighters lost their lives, contributing to the total loss of 438 million USD (Zhang et al., 2024). Fires also rank second in terms of causes of maritime insurance claims, amounting to 18% of all claims, in both number and amount (Wang et al., 2021).

Figure (1) illustrates the number of container fire casualties. It has been noticed that the number of container fire casualties in 2019 was 31 fire accidents, which dropped to 25 accidents in 2020 before rising again to 36 in 2021 (Metwalli, 2022), revealing the importance of identifying root causes behind those rates in general and identifying solutions for future prevention.

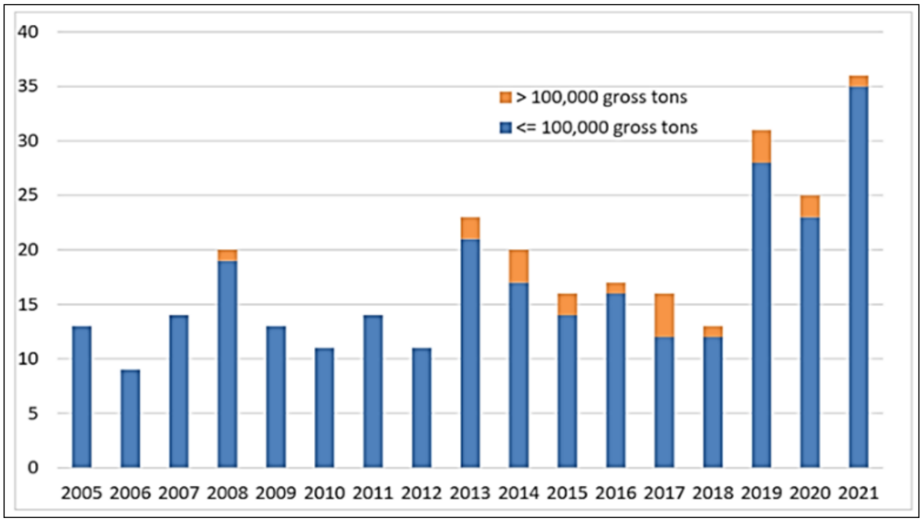

Figure (1) : Container vessel fires- occurrence per year (Metwalli, 2022)

Considering the evidence, the central problem dealt with in this research is that the risk of fire on vessels is ever-present, even with the advent of modern technologies and additional safety regulations. The issue is exaggerated with the size and capacity of ultra-large container vessels (ULCVs). These vessels continue to adhere to the same safety design principles and neglect the evolving nature of fire-related hazards and the safety and protection of the crew. The literature, however, is focused on the traditional aspects, such as human error and explosions onboard however, are emerging and possessing high importance. Insufficient fire-detecting and fire-monitoring systems declared and/or undeclared dangerous goods stowed onboard, and the fire risks due to the stacking of containers are overlooked. The study is meant to address the interaction of these aspects in determining the probability and magnitude of the fire on ULCVs to improve understanding and assist in formulating efficient preventive and protective measures and policies in the field of maritime transport.

2. Literature Review

2.1 Growth and Challenges of ULCVs

Over the last 25 years, the global container shipping industry has seen an increase in the average ship size. This trend in the construction of ultra-large container vessels has been tied to the pursuit of economies of scale in the industry, as larger ships yield lower costs per TEU transported (Ge et al., 2021; Jungen et al., 2021). Between 2011 and 2021, global container capacity grew by more than 65%; however, the number of vessels in the industry grew only about 9%. This suggests that growth in the container shipping industry results from increasing vessel size rather than adding more vessels (Callesen et al., 2021). The work of Stopford (2009) and Sys (2009) indicates that economies of scale have thresholds, with estimates being around 7500 TEUs. This is because several operational challenges, such as ship efficiency, cost management, and safety issues, arise as vessel size continues to grow (El Adl Ibrahim El Adl & Alamoush, 2026).

The capacity increases of ULCVs, first reported in 2020, as capable of carrying over 23,000 TEUs, have led to changes in port operations and navigation. 2020 has long been noted as a starting point of the pandemic, and the increased capacity of vessels has correlated with the increased flow of globalized trade and the resultant bottlenecks. These include; the depth of the port, the outreach of the cranes, the capacity of the port to handle yard, and pilot training. These vessels impose a greater environmental and structural burden on port systems, leading to trade-offs in project costs and diseconomies of scale and efficiency (Aboud & Badry, 2023).

The cost and environmental burden of keeping these vessels economically operational exerts pressure on port systems to forgo efficiency in the beam and to dig deeper drafts to lessen the trade-offs from the above efficiencies. The increases have a marked cost for the surrounding ecosystems.

2.2 Fire Risks and Incident Patterns Onboard Ships

Fires continue to be one of the top dangers to safety at sea. The operational environment on a ship has many possible fire ignitions sources, including the fuel systems, electrical circuits, combustible cargo, and sealed working spaces, all of which create a fire prone environment (The Nautical Institute, 2023); The severity of the situation can be understood from the historical incident data, fires and explosions represented about 19% of bulk carrier incidents from 1980 to 2010 (Roberts and Marlow, 2005), and almost 10% of all maritime losses from 2006 to 2015 (Allianz Global Corporate & Specialty, 2016).

Fires on ships, like other types of accidents, usually develop rapidly and leave little time for evacuation and emergency actions, which results in higher fatalities (Shichuan et al., 2012). Ship fires, especially those containing hazardous or chemically reactive cargo, can also have serious environmental consequences (Baalisampang et al., 2018). The enormous number of damages resulting from fires at sea is also a result of underreporting, which is a common problem in maritime safety data (Hassel et al., 2011).

2.3 Major Causes of Maritime Fires and Explosions

2.3.1 Human Error

Based on ABS (2003) statistics, Baker and McCafferty (2005) argue that there is no disputing that human mistakes made at sea are the leading cause of marine accidents, consisting of approximately 80 to 85% of the documented cases in accident reports across different jurisdictions. Under-reporting errors result from several factors, such as fatigue, lack of proper training, and failure to follow established operational guidelines (Wagenaar and Groeneweg, 2005). Reason (2000) arranges such errors into the two categories of ‘active failures’ (unsafe acts by crew) and ‘latent failures’ (systematic deficiencies in organization, i.e., policies, training, or provision of ineffective tools).

According to Apostol-Mates and Barbu (2016) and Class (2010), such deficiencies do not occur in a vacuum, as they argue that such combinations of errors demonstrate the relationship between the human factor and the organizational safety culture of the maritime system.

2.3.2 Mechanical Failure

Mechanical problems are also a significant source of fires at sea. As noted by Darbra and Casal (2004), mechanical failure is the second most frequent type of accident reported across the maritime sector. Earlier studies indicate that roughly one-third of incidents involving hazardous materials stem from issues such as worn-out components, harsh operating environments, or faults in safety systems (Vilchez et al., 1995; Bejger and Drzewieniecki, 2015). The Allianz report (2016) likewise shows that mechanical breakdowns were responsible for a notable share of vessel losses between 2007 and 2016. In several cases, failures within the firefighting systems themselves, particularly in cargo holds, have triggered severe disasters, as seen in the container vessels MSC Flaminia and Maersk Honam accidents (IUMI, 2023).

2.3.3 Chemical and Thermal Reactions

Self-ignition of dangerous and toxic substances is another noteworthy cause of fire on board vessels. Some estimates suggest that containerized cargo includes hazardous materials in about ten to forty percent of cases (HELCOM, 2002; Munich Re Group, 2002). Dangerous materials that are kept inappropriately or kept in proximity to other, incompatible, chemicals greatly increase the chance of a severe reaction to occurring, as in the case of vessels Hyundai Fortune (2006) and Hanjin Pennsylvania (2002) where a dangerous good such as calcium hypochlorite, as well as the highly flammable, magnesium, some of which was undeclared or mis-declared, substantially contributed to the explosions and subsequent fires (ATSB, 2007; Ellis, 2010).

2.3.4 Electrical Faults

Fires caused by electricity continue to be a major threat, mainly due to faulty connections, overloaded systems, or poor-quality setups (Jadin & Taib, 2012). Studies show that between 50 to 70% of all recorded cases of electrical fires and incidents involve electrical distribution and illumination systems (Babrauskas, 2008; Campbell, 2017). Some overarching causes may be the lack of replacement of aged-out systems, a destructive (as in faulty) modification of the systems, or a complete lack or neglect of the maintenance of systems (McCoskrie, 1990; Baalisampang et al., 2018).

2.4 Fire Identification and Detection Approaches

Conventional methods for detecting fires, such as manual checks, smoke-based alarms, and standard sensor systems, come with notable shortcomings. Human inspection can be inconsistent and prone to fatigue, while sensor networks often have limited coverage and require significant upkeep. Advances in thermal imaging and Computational Fluid Dynamics (CFD) modelling show that heat-detection systems can identify rising temperatures nearly twice as quickly as traditional detectors, offering better early-warning capability for high-risk container fires (Callesen et al., 2019).

2.5 Fire Incidents on High-Tier Containers and Open Decks

Fires that start in high-tier container stacks on open decks pose a serious threat because access to these areas is limited, and heat can spread quickly from one container to another (Callesen et al., 2019). Many of these incidents are tied to hazardous cargo or smoldering materials that go unnoticed until ignition occurs. Their rising frequency, roughly one event every nine days in 2023, has been linked to the growing size of container ships and the ongoing problem of mis declared cargo (Gard, 2024; Allianz, 2024).

Several mitigation measures have been suggested, including placing heat sensors directly inside containers, using infrared monitoring systems, and adopting technologies such as the HydroPen, which drills through container doors to deliver water straight into the affected unit (ClassNK, 2023; EMSA, 2023). Fires on open decks are further complicated by weather conditions like wind and rain, as well as operational mistakes during cargo handling and failures in mechanical or electrical systems (Sanz et al., 2023; Krmek et al., 2022).

2.6 Impacts of Shipboard Fires

The Safety and Shipping Review (2023) notes that fires accounted for 18% of all maritime insurance claims, making them the most expensive cause of vessel losses. Even with advancements in safety technology, the number of reported fire incidents rose to 209 in 2022, marking the highest figure recorded in ten years. High-profile cases, including the mid-Atlantic fire that destroyed more than 4,000 luxury vehicles in 2022, highlight the substantial economic, environmental, and human consequences that result when fire control measures fall short (Zhang et al., 2024).

2.7 Review of Previous Studies

There has been a recent investigation into detection and firefighting techniques used on ships. Ziyang and Roberts (2024) developed a model that uses real-time Ship-Fire Net detection based on YOLOv8n that has a precision and recall of 0.93. Working along similar lines, Sanz et al. (2023) analyzed the risk of ultra-large container vessels subjected to extreme environmental loads and proposed the use of synthetic lines and intelligent mooring systems to cut the risks associated with fire and mooring failures. From the analysis of 19 cargo fire incidents (2010-2020) based on the HFACS-CSCF framework, Metwalli (2022) stated that fire outbreaks can be linked primarily to undeclared dangerous goods. That same concern was stated earlier by Krmek et al. (2021), who claimed that existing firefighting means on container ships do not meet the demands of the situation and urged the need for drastic changes to the framework and technology. Callesen et al. (2021) analyzed and suggested changes to the CFD model to detect early fire and smoke, composed of calcium hypochlorite, compressed charcoal, batteries, and divinylbenzene, that are high-risk cargo. There are findings stemming from these, along the lines of Baalisampang et al. (2018) performed a scale meta-analysis on fire and explosion incidents for the period 1990–2015 and emphasized the alternative fuels, including LNG and methanol, potentially being able to mitigate fire risks within the maritime domain.

3. Identified Research Gaps

There will be a lot more research on fire safety. However, a few things will still be left unfinished. Many works will neglect the unique risks that come with the stowage of larger containers on ULCVs. Many more works will attempt, but simply fail, to create comprehensive risk assessment models that fully incorporate the role of human error, undeclared hazardous cargo, and limitations of detection technologies. Because of a lack of documented fire incidents, there will be a lack of operational evidence to improve systems. Given everything described, this research will focus on overlooked factors to improve safety systems operationalized through data that will be targeted to the reduction of fire incidents and the factors that contribute to fire incidents and their consequences on ULCVs.

4. Research Design and Methodology

This study adopts a quantitative research methodology designed to analyze the relationship between human error, undeclared dangerous goods, and the absence of fire detection technologies, and their impact on fire occurrences in high-tier containers on ULCVs.

The main research tool was a structured questionnaire developed based on previous literature and expert consultation. It consisted of 46 statements distributed across four constructs: Human Error (13 items), Dangerous Goods (11 items), Fire Detection Technology (9 items), and Fire Risks (13 items).

The answers were evaluated based on a five-point Likert scale with values of “Strongly Disagree” (1) to “Strongly Agree” (5). Both content and face validity stem from the pilot study that helped adjust wording and relevance of the items.

The study population consisted of deck officers and marine engineers with experience in operations aboard ULCVs. Using simple random sampling, 156 valid responses were gathered electronically using Google Forms. This response rate surpassed the minimum size needed to ensure statistical power for the regression analysis (15 responses for each variable), which preserved the representativeness and the analytical depth as well (Helal, 2021).

The primary source of data was the questionnaires for the primary dataset, while the secondary dataset was derived from academic journals and technical papers. Using the Statistical Package for Social Sciences (SPSS V26), data were subjected to analysis, which consisted of both descriptive measures of descriptions and inferential statistics based on a significance value of 0.05. To check the validity of the questionnaire, a test for internal consistency for each of the items was done using Pearson’s correlation coefficient. Reliability, on the other hand, was determined using Cronbach’s alpha, where values of 0.70 and above were accepted as good indicators of internal consistency.

5. Hypotheses Test

5.1 First Hypothesis

H1: *Human error has a significant impact on ULCVs cargo fire occurrence.* To test this hypothesis, a multiple regression analysis was applied to assess the influence of the three dimensions of human error, physical and psychological conditions, compliance and organizational errors, and decision-making and judgment errors on ULCVs cargo fire occurrence.

Table 2 presents regression results.

Table (2) Multiple Regression Analysis of Human Error on Container Ship Cargo Fires Occurrence.

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	ANOVA Sig
	B	Std. Error	Beta			
(Constant)	.726	.157		4.613	.000	0.000
physical and psychological conditions for ship staff	.270	.082	.290	3.280	.001	R^2 = 0.780
Compliance and Organizational Errors	.300	.092	.321	3.274	.001	
Decision-Making and Judgement Errors	.284	.095	.306	2.994	.003	

The **ANOVA significance value (Sig = 0.000)** confirms the overall model significance at the 0.05 level. All three predictors had **positive and statistically significant effects**:

- Physical and psychological conditions (B = 0.270, t = 3.280, p = 0.001)
- Compliance and organizational errors (B = 0.300, t = 3.274, p = 0.001)
- Decision-making and judgment errors (B = 0.284, t = 2.994, p = 0.003)

The R^2 value of 0.780 shows that human error dimensions account for 78 % of the variation in cargo fire incidents, which reflects a strong level of explanatory power within the model. Based on this result, H1 is confirmed, indicating that human error has a considerable influence on the occurrence of fires aboard ULCVs.

5.2 Second Hypothesis

H2: *Undeclared dangerous goods have an impact on ULCVs cargo fire occurrence.* A multiple regression analysis was conducted to measure the impact of handling stowage errors and declaration of errors on fire incidents.

Table (3) Multiple Regression Analysis of Undeclared Dangerous Goods on ULCVs cargo fire occurrence

Model	Unstandardized Coefficients		Standardized Coefficients	T	Sig.	ANOVA Sig
	B	Std. Error	Beta			
(Constant)	.667	.154		4.335	.000	0.000
Handling and Stowage Errors	.410	.108	.437	3.806	.000	R^2 = 0.791
Documentation and Declaration Errors	.436	.108	.464	4.041	.000	

The ANOVA significance value (0.000) verifies the model's validity, with $R^2 = 0.791$, meaning 79.1% of fire occurrence variance is explained by the predictors. Both factors have statistical significance:

- Handling and stowage errors ($B = 0.410$, $\beta = 0.437$, $t = 3.806$, $p < 0.001$)
- Documentation and declaration errors ($B = 0.436$, $\beta = 0.464$, $t = 4.041$, $p < 0.001$)

These results confirm that mishandled or undeclared hazardous goods are major contributors to cargo fires. Accordingly, the second hypothesis is accepted, with the need for stricter control and accurate declaration of dangerous cargoes.

5.3 Third Hypothesis

H3: *Fire Detection Technology has an impact on ULCVs cargo fire occurrence.*

A simple regression analysis was performed to examine the relationship between fire detection technology and fire incidents.

Table 4 shows that the model is highly significant (**ANOVA Sig = 0.000**), with **R^2 = 0.836**, indicating that 83.6% of the variation in fire occurrence is explained by detection of technology efficiency. The regression coefficient ($B = 0.873$, $\beta = 0.915$, $t = 28.155$, $p < 0.001$) confirms a strong positive impact.

Table (4) Simple Regression Analysis of Fire Detection Technology on ULCVs cargo fire occurrence

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	R	R^2	ANOVA Sig
	B	Std. Error	Beta					
(Constant)	.619	.133		4.640	.000	.915	.836	.000
Fire Detection Technology	.873	.031	.915	28.155	.000			

Accordingly, the third hypothesis is supported that advanced fire detection technology reduces the likelihood of cargo fires, which may enhance maritime safety.

6. Recommendations

- Improvement of the human element of the organization will require the development of a holistic approach to psychological support, ongoing safety training, plus the application of modern systems for the detection, assessment, and control of errors in the system before they occur.
- Strengthening the mechanisms put in place for the declaration of cargo and the subsequent handling of the cargo should include the adoption of stringent regulatory frameworks, supported by AI-powered inspection systems and real-time control systems to detect and classify hazardous materials that are either undeclared or improperly declared.
- There should be a commitment to the adoption of advanced technologies for the detection and prevention of fires, which should include automated systems for the activation of alarms, systems for the capture of images along a thermal spectrum, and smart containers that are designed to monitor their internal status.
- Expanded development of experiential learning and competence training is possible for the crew through structured, systematic approaches to mentoring and simulation, which are sufficiently realistic to improve situational awareness and the competency of emergency response management systems.
- Updating international maritime regulatory instruments, particularly the Safety of Life at Sea (SOLAS) Convention and the International Maritime and Dangerous Goods (IMDG) Code, should incorporate a requirement for the electronic verification of cargo. It should also tie vessel certification to the installation, verification, and periodic testing of an advanced, tiered fire detection and suppression system.

7. Conclusion

This study addressed the reasons for viable solutions to the occurrence of fires in high-tier containers of (ULCVs). The data indicated that the human factor, the presence of undeclared dangerous cargo, and not having sufficient fire detection systems are the main causes that affect the occurrence and severity of the fire in the containers. Out of the stated variables, the human factor, especially poor decision-making, fatigue, and compliance with procedures, was the most significant reporting in nearly 78% of the cases. Furthermore, the study also indicated that improper handling and undeclared dangerous goods increase fire risk, and the absence of fire detection systems.

The new integrated safety management techniques with real-time monitoring and human factor engineering focus will be needed, according to the results. Utilization of AI-assisted real-time monitoring of containers, thermal imaging systems, and smart containers can bolster the early warning and response to fire threats to a great extent. At the same time, the SOLAS Convention and the IMDG Code must be updated to incorporate additional electronic cargo manifest requirements, fire detection and suppression systems at various locations, and fire detection and suppression systems to contain operational and fire safety threats.

Also, this assists ship operators, classing societies, and regulators in working with new documentation and evidence on maritime safety. The fire loss in maritime safety and shipping can be made safer, and the loss of fire can be safer and more sustainable shipping to the world.

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Reducing Marine Oil Pollution through International Regulation: An Empirical Assessment of MARPOL Annex I Enforcement in Egypt

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المستخلص

لا يزال التلوث الزيتي الناجم عن أنشطة السفن يمثل تحديًا بيئيًا ملحًا في البيئة والممرات المائية المصرية. تبحث هذه الدراسة في مدى ارتباط فعالية إنفاذ الملحق الأول من الاتفاقية الدولية لمنع التلوث من السفن (ماربول) في مصر بتحسن نتائج الحد من التلوث الزيتي، كما تسعى إلى الكشف عن الآليات المؤسسية المؤثرة في فعالية التنفيذ. تعتمد الدراسة منهجًا تكامليًا قائمًا على أساليب كمية ونوعية (المنهج المختلط المتقارب)، يجمع بين تحليل سلاسل زمنية وطنية لبيانات حوادث التسرب المبلغ عنها خلال الفترة (١٩٩٠–٢٠٢٣)، وتحليل السلاسل الزمنية المقطعية (المتقطعة) المرتبطة بمحطات تنفيذ رئيسية، وتحليل متعدد المتغيرات لبحث العلاقة بين نتائج التسرب وعوامل مرتبطة بالإنفاذ (نشاط التفتيش، متابعة الإجراءات التنفيذية، وتوافر مرافق الاستقبال)، إضافة إلى التحليل المكاني باستخدام نظم المعلومات الجغرافية وتقدير كثافة النواة في ٣٣ منطقة ساحلية وميناية، وتحليل موضوعي لعدد ٢٥ مقابلة شبه مُنظَّمة مع جهات معنية.

تشير النتائج عبر مختلف محاور الدراسة إلى تحسن ملحوظ في المخرجات خلال المراحل المتأخرة من التنفيذ مقارنة بالمراحل الأولى، مع تحقيق نتائج أفضل عند تكامل دورات الإنفاذ وتوافر البنية التحتية لمرافق الاستقبال بصورة عملية. كما يكشف التحليل المكاني عن استمرار وجود ممرات ومناطق اقتراب من الموانئ ذات مخاطر مرتفعة، بما يدعم تبني نهج قائم على تقييم المخاطر في توجيه أنشطة التفتيش والرصد.

وتبرز نتائج المقابلات أهمية وضوح الأدوار والتنسيق بين الجهات، وتعزيز القدرات الفنية والبشرية، وترسيخ مصداقية الإنفاذ، وتطوير نظم المعلومات للكشف والمتابعة. وتوصي الدراسة بتعزيز المسارات المتكاملة بين الإنفاذ والبنية التحتية ونظم المعلومات، وإضفاء الطابع المؤسسي على استهداف التفتيش بناءً على بؤر المخاطر، وتوحيد آليات الإبلاغ وتكامل البيانات بين الجهات، وإعطاء أولوية لبناء القدرات في المناطق عالية المخاطر والمحدودة الموارد، بما يسهم في خفض التلوث الزيتي الناجم عن السفن في مصر بصورة أكبر.

الكلمات البحثية: الملحق الأول من اتفاقية ما ربول - التلوث الزيتي الناجم عن السفن؛ الحد من التسربات النفطية - رقابة دولة الميناء - مرافق الاستقبال؛ قناة السويس - مصر؛ الحوكمة البيئية.

Abstract

Oil pollution from ship activities still constitutes a pressing concern for the Egyptian environment and waterways. This research examines whether the effectiveness of the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex I in Egypt is linked to improved oil pollution outcomes and seeks to uncover institutional mechanisms influencing the effectiveness of implementation. A convergent mixed-methods approach combines national time-series analysis of reported spill outcomes (1990-2023) with segmented (interrupted) time-series reasoning around critical implementation milestones, multivariate analysis associating spill outcomes with enforcement-related factors (inspection activity, enforcement follow-through, and reception capacity availability), geographic information system hotspot mapping with kernel density estimation in 33 port/coastal regions, and thematic analysis of 25 semi-structured interviews with relevant authorities. Across all strands, results support better outcomes in later stages of implementation compared to earlier stages, with greater success when enforcement cycles and reception infrastructure are practically accessible.

Spatial analysis indicates persistent higher-risk corridors and port-approach zones, supporting a risk-based interpretation of enforcement and monitoring needs. Interview evidence emphasizes the importance of role clarity and inter-agency coordination, technical and human capacity, enforcement credibility, and information systems for detection and follow-up. The study recommends strengthening integrated enforcement–infrastructure–information pathways, institutionalizing hotspot-informed inspection targeting, standardizing inter-agency incident reporting and data integration, and prioritizing capacity building in high-risk and resource-constrained locations to further reduce ship-source oil pollution in Egypt.

Keywords: MARPOL Annex I; ship-source oil pollution; oil spill reduction; port State control; reception facilities; Suez Canal; Egypt; environmental governance; maritime law; mixed-methods

1. Introduction

Oil pollution from ship operations remains a persistent environmental risk along Egypt's maritime spaces, particularly near the Suez Canal corridor and adjacent port approaches(Kostianaia et al., 2020). While major spill events have declined in recent years, evidence indicates that chronic small-scale discharges (e.g., oily bilge/ballast residues and operational releases) continue to occur, especially in areas where enforcement capacity and port waste reception services are limited (Kostianaia et al., 2020; Abou El-Magd, 2021).

These spills create real-world ecological and economic costs for coastal ecosystems and regions that rely on tourism (Hoarau, 2022). The ratification of MARPOL 73/78 Annex I by Egypt created a legal system for the management of oil discharge emissions from vessels; nevertheless, legal transposition does not automatically ensure compliance (Carpenter & Kostianoy, 2018). The success of implementation depends on the credibility of inspections, the presence of reception facilities, coordination between agencies, and the ability to monitor and prosecute non-compliance (Ramahlo, 2022; Carpenter & Kostianoy, 2018). In Egypt, the enforcement of Annex I is the responsibility of several agencies, which has been identified as a possible source of confusion about the effectiveness of implementation (Kostianaiā et al., 2020). This research examines the link between the implementation and enforcement of Annex I in Egypt and the effects of oil spill emissions by combining (i) trend evidence from spill data and (ii) institutional evidence from enforcement mechanisms.

2. Literature Review

2.1 Effectiveness of MARPOL Annex I and the Role of Enforcement

There is a consensus in the literature that MARPOL Annex I has the potential to reduce ship-based oil pollution significantly, but its effectiveness relies largely on the enforcement capacity rather than mere ratification (Karim, 2016; Carpenter & Kostianoy, 2018). The literature also suggests that the port States that perform regular and credible Port State Control inspections, have sound verification of Oil Record Books, and have consistent sanctioning policies perform better in terms of environmental results. Conversely, the literature shows that there are often implementation deficits in developing port States that lack regular inspections, have weak evidence trails, or lack sufficient deterrent effects of sanctions (Kostianaia 2020; Cui 2024).

2.2 Determinants of Compliance: Reception Facilities, Detection, and Auditability

One of the most consistent results in the literature is that compliance with Annex I is highly dependent on operational feasibility. Receiving oily waters at shorelines is required, as lack of capacity could raise the attractiveness of illegal dumping (Carpenter & Kostianoy, 2018). On the other hand, the role of auditing and detection is also important, as a compliance mechanism based solely on paper documents without verification can be readily defeated (Jiang & Cao, 2011). The literature emphasizes the increasing role of satellite surveillance, ship tracking, and inter-agency reporting systems in raising the attractiveness of detection and the success of enforcement actions (Abou El-Magd, 2021).

3. Egypt: Institutional and Enforcement Context

The use of Annex I in Egypt is characterized by the existence of several actors with overlapping or contiguous mandates, including the Egyptian Environmental Affairs Agency (EEAA), the Egyptian Authority for Maritime Safety (EAMS), the Suez Canal Authority (SCA), and some naval or security bodies in specific regions (Hassan, E. A. 2020; MEEA, 2016). As per the current literature, the predictability of inspection and enforcement can be affected by overlapping mandates, which may lead to confusion among the leadership, duplication of efforts, and a lack of follow-through (Kostianiiaiaia et al., 2020). Some of the key operational challenges that have been identified include the inadequacies of reception facilities, particularly in the Red Sea ports identified, which contribute to the problem of illegal discharges by ships that do not wish to incur delays or costs (Kostianiiaiaia et al., 2020; Baghdady, 2024).

4. Empirical Oil-Spill Trends in Egypt (1990-2023)

Notwithstanding the available data on the number of incidents and the amount of oil spills, there has been a significant decrease in the number of major oil spill incidents, with the most significant improvements being recorded in the years that followed 2010 (Abdelkader, 2018).This is largely due to improvements in the inspection process and increased scrutiny of compliance documentation (Etkin, 2023; Abou El-Magd, 2021).

Spatial data also confirms that increased surveillance and tracking efforts can lead to a reduction in spill hotspots by increasing the probability of detection and facilitating faster enforcement response (Abou El-Magd, 2021). At the same time, there are a number of sources that confirm the difficulty in completely eliminating low-level operational spills, especially in areas where reception points are limited or enforcement is not coordinated (Kostianaia et al., 2020).

5. Regional Benchmarking

Regional benchmarking results show that Egypt's Annex I implementation indicators are more favorable than those of some regional countries, although regional performance is variable and depends on the capacity of countries (World Bank, 2021; UNEP, 2020). In this paper, regional comparison is used only as a point of reference to determine whether the observed Egyptian performance is in line with the expected performance related to improvements in enforcement capacity.

6. Synthesis and Research Gap

The existing literature provides three applicable findings. First, Annex I performance is not only dependent on the adoption of the treaty but also dependent on the credibility of inspections, probability of detection, and waste reception capacity (Karim, 2016; Carpenter & Kostia͡noĭ, 2018).

Second, the presence of port states may have limitations in compliance because of institutional fragmentation and capacity, resulting in inconsistent performance (Mona et al., 2019). Third, Egypt-specific studies indicate a lack of coordination and facilities but do not normally link these to a spill outcome assessment (Kostianaia et al., 2020; Abou El-Magd, 2021).

The current Egypt-centric literature is basically descriptive, either based on pollutant data or treaty explanations, and does not normally combine spill trend data with institutional enforcement factors that may shed light on spill reduction and continued discharges (MEEA,2016). This study will address this problem by employing a mixed-methods design that combines spill trend data with enforcement factors such as inspection activity, reception facility adequacy, monitoring capacity, and interagency cooperation. (Bakr et al., 2024)

Oil pollution has impacts on the Egyptian coastal environment and also has economic costs in tourism and fishing, especially in the Red Sea resort areas. The presence of hydrocarbon resources in sediments and operational spills indicates the need for effective compliance mechanisms that go beyond the ratification of treaties (El-Sayed & Hassan, 2019; Zhao et al., 2025). Thus, the assessment of the effectiveness of Annex I treaty enforcement is not only a technical matter but also a governance matter with special implications.

7. Study Approach and Expected Practical Value

By analyzing the trends of temporal spills and comparing them with the conditions of enforcement and the statements of stakeholders, this paper reveals the factors that are most closely related to the reduction of oil spills in the implementation of Annex I in Egypt and the areas that still allow small-scale spills. The results of this paper can help improve specific areas.

8. Research Methodology

8.1 Research Design

This study adopts a convergent mixed-methods research design to assess whether the implementation and enforcement of MARPOL 73/78 Annex I in Egypt are associated with improved ship-source oil pollution outcomes along the Mediterranean coast, the Suez Canal corridor, and the Red Sea/Gulf of Suez. Quantitative and qualitative strands are conducted in parallel and integrated through systematic triangulation.

The quantitative component examines oil-spill outcomes over the period 1990–2023, focusing on (i) annual spill frequency, (ii) reported spill volumes were available, and (iii) spatial distribution of incidents across 33 port and coastal areas. The analysis combines national time-series assessment, panel data analysis of port areas, and hotspot mapping using Geographic Information Systems (GIS). Where possible, reported incidents are cross-validated with satellite remote-sensing data (MODIS and Sentinel-1 SAR) to enhance the precision of detection.

The qualitative component of the analysis involves a structured assessment of the national legal and policy frameworks in relation to the application of Annex I, as well as semi-structured interviews and observation visits to the ports. This component of the analysis seeks to offer insight into the reality of enforcement and to interpret the findings in the context of realities of enforcement.

The combination of the results is done through a joint display (triangulation matrix) that combines spill trends, spatial patterns, regulatory milestones, and perceptions of stakeholders.

8.2 Analytical Framework

The framework of the research is structured around three interrelated dimensions of analysis that link obligations, enforcement capacity, and environmental outcomes.

Regulatory Dimension

The regulatory dimension of analysis is concerned with the transposition of Annex I obligations into Egyptian law and policy, with a focus on the key steps of implementation, such as Law No. 4 of 1994 and Ministerial Decree No. 73 of 2013. The analysis will be focused on discharge controls, inspection rights, document checks, reporting obligations, and penalty provisions regarding the prevention of oil pollution.

Institutional Dimension

This category assesses the enforcement regime in which Annex I commitments are to be enforced, and the respective roles of the EEAA, EAMS, and the Suez Canal Authority. The key indicators are the allocation of responsibilities with respect to inspections, cooperation among agencies, the procedure for carrying out inspections, the procedure for enforcing follow-up actions, and the limitations of enforcement with respect to human resources, technical capacity, and exchange of information.

Environmental-Compliance Outcomes Dimension

This dimension evaluates the results of implementation based on the following indicators: (i) the number of oil spills per year, (ii) the volume of spills where possible, and (iii) the concentration of spills per region using GIS hotspot analysis. These indicators allow the assessment of the persistence of the risk of spills over time and space. Taken together, these dimensions operationalize the implementation of Annex I as a process whereby legal commitments are converted into environmental results.

8.3 Data Sources and Sampling

The main data is collected from three main sources:

(i) administrative records related to oil spill events, inspections, and enforcement, collected from EEAA, EAMS, and IMO (1990-2023);

(ii) twenty-five semi-structured interviews carried out in 2023 with purposively selected officials from EEAA, EAMS, and Suez Canal Authority.

(iii) observations at ports in Suez, Port Said, and Hurghada to determine the availability and functionality of oily-waste reception facilities.

The quantitative data are structured into 33 port and coastal areas, which include Egypt's Mediterranean coast (n = 12), the Suez Canal area (n = 9), and the Red Sea/Gulf of Suez (n = 12). These areas are determined by administrative port boundaries and surrounding operational areas where spill and enforcement data are available.

The secondary data include peer-reviewed literature related to Egypt, regional compliance rates, and satellite remote sensing images used for contextual validation.

8.4 Data Validation and Reliability

To enhance the accuracy of the data, a two-step verification process is adopted. First, the oil spill records are verified based on date-location matching criteria among the EEAA, EAMS, and IMO datasets. Later, for the post-2000 period, the recorded incidents are verified through MODIS and Sentinel-1 SAR satellite images within a temporal window of ±3 days and a spatial window of ≤10km.

Instead of removing observations with extreme values by default, sensitivity analysis is conducted through re-estimation with and without extreme years to assess robustness.

8.5 Overview of Data Inputs and Analytical Purpose

Table.1 provides a concise summary of the relationship between data sources, time coverage, geographic focus, and analytical purpose, providing a comprehensive view of the empirical inputs that inform the mixed-methods design.

Table 1. Data

Data Type	Source	Temporal Coverage	Spatial Unit / Sample	Rationale
Oil spill frequency & volume (reported incidents)	EEAA, EAMS, IMO	1990–2023	33 port/coastal areas (Mediterranean n=12; Suez Canal corridor n=9; Red Sea/Gulf of Suez n=12)	Baseline for time-series trend analysis and outcome measurement (frequency and volume where available)
Satellite imagery (MODIS; Sentinel-1 SAR)	NASA; ESA	2000–2023	250 m–10 m pixels; matched to reported incidents (±3 days; ≤10 km)	Independent validation/corroboration of reported incidents and spatial extent (post-2000)
Legal and policy texts (Annex I transposition)	Official Gazette; Ministry of Environment	1994–2023	National instruments (e.g., Law No. 4/1994; Decree No. 73/2013)	Establish regulatory variables and implementation milestones used in the institutional/legal analysis
Institutional enforcement and coordination records	EEAA; EAMS; SCA	2005–2023	3 operational zones (Mediterranean; Suez Canal corridor; Red Sea/Gulf of Suez)	Assess enforcement architecture, inter-agency coordination, inspection workflows, and follow-up procedures by zone
Port observation visits (reception facilities and procedures)	Direct observation (author); port authorities	2023	3 ports (Suez; Port Said; Hurghada)	Assess availability and functionality of waste reception arrangements and operational constraints
Expert interviews (N=25)	EEAA (n=9); EAMS (n=8); SCA (n=8)	2023	Purposive; roles: inspectors (n=7), compliance/response (n=6), reception oversight (n=4), legal/policy (n=4), senior managers (n=4)	Capture experiential evidence on Annex I enforcement barriers, coordination gaps, and compliance behavior

Data Type	Source	Temporal Coverage	Spatial Unit / Sample	Rationale
Oil spill frequency & volume	EEAA, EAMS, IMO	1990–2023	33 port areas	Baseline for quantitative trend modelling
Satellite imagery (MODIS, Sentinel-1 SAR)	NASA & ESA	2000–2023	250 m–10 m pixels	Independent validation of reported incidents
Legal and policy texts	Official Gazette, Ministry of Environment	1994–2023	—	Establish regulatory variables
Institutional data	EEAA & SCA	2005–2023	3 main zones	Assess inter-agency efficiency
Expert interviews (N = 25)	EEAA, EAMS, SCA officials	2023	Purposive	Capture experiential knowledge and enforcement barriers

Sources, temporal coverage, and analytical purposes

The table above specifies the empirical inputs used in the research and the role of each input in the mixed-methods design. Administrative records and official documents offer the longitudinal framework for spill outcome description and enforcement actions during the time of the research, while satellite data

Table 1 illustrates the role of administrative records and official documents in offering the longitudinal framework for spill outcome description, satellite imagery in offering spatial validation, legal and policy texts in offering regulatory milestones, and interviews and port observations in offering institutional context for the interpretation of quantitative and spatial pattern.

8.6 Methodological Integration

The quantitative and qualitative analysis are carried out separately and then combined through triangulation. The quantitative findings identify when and where the changes in the outcomes of spills happen, and the qualitative findings explain how and why the changes are associated with enforcement practices, institutional coordination, and capacity. The combination of the two improves inferences by linking the observed environmental outcomes to the possible mechanisms of enforcement instead of relying on one source or technique.

9. Data Collection and Analysis

This section describes the quantitative and qualitative analysis methods used to evaluate the outcomes of MARPOL Annex I implementation in Egypt. The quantitative part of the analysis estimates the outcomes of oil spill changes at major implementation milestones, while the qualitative part of the analysis explains the institutional mechanisms and implementation challenges using document analysis and interviews.

Findings are integrated using a triangulation matrix, and robustness is assessed through standard diagnostic and sensitivity checks.

9.1 Quantitative analysis

The quantitative component evaluates whether (i) oil-spill outcomes declined following Egypt's MARPOL Annex I–aligned regulatory milestones and (ii) whether enforcement and port-capacity variables predict spill outcomes across ports and time. Analyses are conducted using (a) a national annual time series (1990–2023) and (b) a port-area-year panel (1990–2023) across 33 port/coastal areas (Mediterranean n=12; Suez Canal corridor n=9; Red Sea/Gulf of Suez n=12). Segmented (interrupted) time-series regression is used for milestone evaluation (Wagner et al., 2002; Lopez Bernal et al., 2017), count-data models are used for spill incidents (Cameron & Trivedi, 2013), and kernel density estimation is used for hotspot mapping (Silverman, 1986; Esri, n.d.). For contextual regional benchmarking, the study reports the MARPOL Annex I implementation index published by Badr (2023) as a secondary reference; this index is not constructed from the present study's administrative datasets.

9.1.1 Descriptive change (period comparison)

A simple descriptive effect size is computed as the percentage change between a baseline period and a comparison period (Stock & Watson, 2020):

$$\Delta\% \;=\; \left(\frac{\bar{Y}_{post} - \bar{Y}_{pre}}{\bar{Y}_{pre}}\right) \times 100$$

Where:
$\Delta\%$= percentage change between periods;
$\bar{Y}_{pre}$= mean annual outcome in the baseline period (e.g., pre-1994);
$\bar{Y}_{post}$= mean annual outcome in the comparison period (e.g., post-1994);
Ymay be spill frequency (incidents/year) or spill volume (units as reported in official records).

9.1.2 Interrupted time-series segmented regression (policy milestone effects)

To estimate changes associated with key milestones (1994 and 2013), annual spill outcomes are modeled using segmented regression (Wagner et al., 2002; Lopez Bernal et al., 2017):

$$Y_t \;=\; \beta_0 + \beta_1\, time_t + \beta_2\, post1994_t + \beta_3\, time1994_t + \beta_4\, post2013_t + \beta_5\, time2013_t + \varepsilon_t$$

Where:
Y_t= national annual spill outcome in year t(spill incidents or spill volume);
$time_t$= time trend (e.g., $t = 1$for 1990, …, $t = 34$for 2023), or calendar year coded consistently;
$post1994_t$= 1 for years $t \geq 1994$, otherwise 0;
$time1994_t$= 0 for years before 1994; $(time_{1994})$for years $t \geq 1994$;
$post2013_t$= 1 for years $t \geq 2013$, otherwise 0;
$time2013_t$= 0 for years before 2013; $(time_{2013})$for years $t \geq 2013$;
β_0= baseline intercept;

β_1= baseline pre-1994 trend (slope);
β_2= immediate level change after 1994;
β_3= change in slope after 1994;
β_4= immediate level change after 2013;
β_5= change in slope after 2013;
ε_t= error term.

Autocorrelation and heteroskedasticity are addressed using HAC/robust inference as appropriate (Newey & West, 1987; White, 1980).

9.1.3 Panel model linking enforcement conditions to spill outcomes

When port-area-year observations are available, spill outcomes are related to enforcement proxies using a fixed-effects panel specification (Wooldridge, 2010; Cameron & Trivedi, 2013). For incident counts, a fixed-effects count model with log link is used:

$$E\,[X_{it}] \;=\; exp\,(\beta_3\, Reception_{it})$$

Where:

Y_{it}= spill outcome for port/coastal area $i$in year t(incident count, or volume where modeled);
α_i= port-area fixed effect (controls time-invariant differences across areas);
δ_t= year fixed effect (controls common annual shocks/trends);
$Inspect_{it}$= inspection frequency proxy in area i, year t;
$Enforce_{it}$= enforcement actions proxy in area i, year t;
$Reception_{it}$= reception capacity proxy in area i, year t;
$\beta_1, \beta_2, \beta_3$= estimated associations between enforcement proxies and spill outcomes.

Robust standard errors are used, and sensitivity checks may include alternative count specifications (e.g., Poisson FE; negative binomial sensitivity) as described in the robustness table.

9.1.4 Spatial hotspot mapping (kernel density estimation)

Spill clustering is mapped using kernel density estimation (Silverman, 1986) as implemented through ArcGIS Pro’s kernel density tool (Esri, n.d.):

$$\hat{f}_h(s) \;=\; \frac{1}{n\,h^2}\sum_{i=1}^{n} k\,\left(\frac{d(s, s_i)}{h}\right)$$

Where:

$\hat{f}_h(s)$= estimated spill-event intensity (density) at location s;
s= spatial location (map coordinate) in the study region;
s_i= location of spill event i;
n= number of spill events included for the chosen period;
h= bandwidth (search radius) controlling smoothing;

$d(\cdot)$= distance metric used by the GIS setting;
$K(\cdot)$= kernel function weighting nearby points more than distant points.

Bandwidth/cell-size settings are reported and hotspot stability is tested using alternative defensible bandwidth values (Silverman, 1986; Esri, n.d.)

9.2 Qualitative analysis

Qualitative evidence is used to explain implementation mechanisms and interpret quantitative patterns. Two sources are analyzed: (i) document analysis of national legal/policy texts and institutional records, and (ii) semi-structured interviews with relevant officials and practitioners.

Document analysis follows established qualitative procedures for systematic extraction and triangulation of information from documents. Interview and document materials are coded using thematic analysis. The codebook combines (a) deductive codes aligned with Annex I enforcement functions (inspection routines, documentation verification, reception facility access, enforcement follow-up, monitoring/reporting, inter-agency coordination) and (b) inductive codes that emerge from interview narratives and observation notes.

9.3 Integration of quantitative and qualitative findings

A convergent mixed-methods approach is applied: quantitative and qualitative analyses are conducted separately and then merged using a joint display (triangulation matrix), which is a recommended method for transparent integration in mixed-method studies (Fetters et al., 2013). The matrix aligns quantitative results (e.g., post-milestone trend changes; hotspot persistence; predictor associations) with qualitative themes (e.g., coordination gaps, reception-facility barriers, inspection bottlenecks). Divergence across evidence streams is explicitly analyzed and reported as potential underreporting, definitional mismatch, or institutional/data limitations.

9.4 Validation, reliability, and robustness

Quantitative robustness. Robustness is assessed using alternative model forms for spill counts (Poisson vs. negative binomial), alternative intervention windows where justified, and re-estimation with and without extreme years (sensitivity checks) rather than automatic outlier deletion (Yaseen, 2018). Heteroskedasticity-robust inference is applied and where serial correlation is present, HAC estimators are used. Where relevant, serial correlation diagnostics can be reported (MacKinnon, 2012).

Data validation and triangulation.

Reported incidents are cross-checked across administrative sources (EEAA/EAMS/IMO) when overlap exists, and for the post-2000 period, remote sensing (MODIS/Sentinel-1 SAR) is used as an independent corroboration layer with a documented temporal/spatial matching window. Port observation visits are used to validate claims regarding reception-facility functionality and operational constraints.

Qualitative reliability.

Reliability is supported through codebook documentation, audit trails linking themes to underlying evidence, and re-coding checks. When multiple coders are used, agreement can be assessed using established content-analysis reliability procedures (Krippendorff, 2018). If the study includes any multi-item survey scales, internal consistency can be evaluated using Cronbach's alpha (Robinson,2018); otherwise, interview-based thematic analysis reliability is documented through codebook stability and audit procedures.

10. Discussion and Analysis

10.1 Overview of Analytical Approach

This section evaluates whether the implementation of MARPOL Annex I in Egypt is associated with improved oil-pollution outcomes during the period 1990–2023. The analysis combines four different strands of evidence: (i) national time-series trends, (ii) panel associations between enforcement conditions and spill outcomes for port areas, (iii) hotspot analysis employing GIS, and (iv) qualitative institutional evidence from interviews and document analysis.

The analysis is organized around three key questions: what have been the outcomes of spills over time, where have geographic changes occurred, and how have enforcement and institutional mechanisms affected these changes.

10.2 Temporal Trends in Oil-Spill Outcomes

The analysis combines four different types of evidence: (i) national time-series trends, (ii) panel associations between enforcement conditions and spill outcomes for port areas, (iii) hotspot analysis using GIS, and (iv) qualitative institutional evidence from interviews and document analysis. The analysis is organized around three key questions: What changes occurred in spill outcomes over time, where did geographic changes occur, and how did the mechanisms of enforcement and institutions bring these changes about.

Table 2. Descriptive period comparisons of oil-spill outcomes and enforcement activity

Period	Avg. annual spills	Avg. reported spill volume (tons)	Enforcement cases	Trend direction (descriptive)
1990–1993 (Pre-MARPOL)*	21	45,000	3	Escalating pollution
1994–2009 (Early enforcement phase)	9	18,000	14	Moderate decline
2010–2023 (Strengthened compliance phase)	4	7,000	26	Strong decline

The average results of spill and enforcement activity during the phases of implementation are shown in Table 2, providing a clear description of the type and timing of change. The interrupted time-series analysis also provides evidence of a structural shift in the results of spill around the important milestones of implementation, particularly those related to improved enforcement and documentation systems. While there is no possibility of establishing causality, the coincidence of changes in the strength of regulation and spill results is significant. The long-term trend in oil-spill incidents is illustrated in Figure 1, which shows a clear downward trajectory consistent with the descriptive and model-based findings.

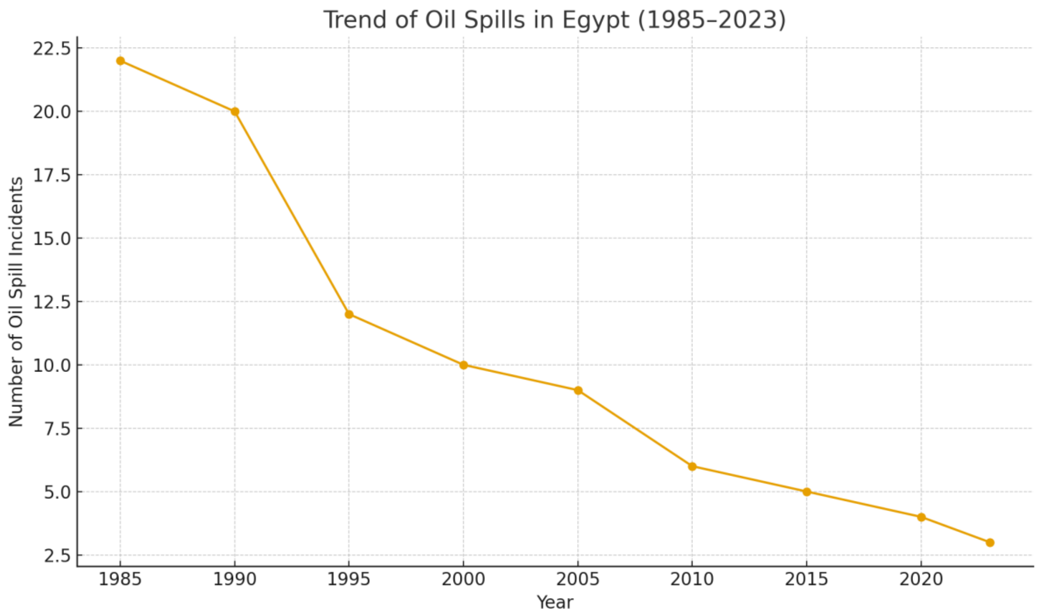


Figure 1. Trend of oil-spill incidents in Egypt (1990–2023)

10.3 Enforcement Conditions and Spill Outcomes

To complement the national trend analysis, this study examines whether variation in enforcement-related conditions is associated with differences in spill outcomes across ports and time. Multivariate analysis focuses on inspection frequency, enforcement actions, and reception-facility availability as key predictors consistent with Annex I compliance logic.

Table 3. Multivariate associations between enforcement-related predictors and spill outcomes

Predictor (standardized)	Standardized β	p-value	Interpretation (academic, non-causal)
Inspection frequency (X_1)	− 0.48	< 0.01	Higher inspection activity is related to worse spill outcomes, consistent with deterrence and improved compliance monitoring.

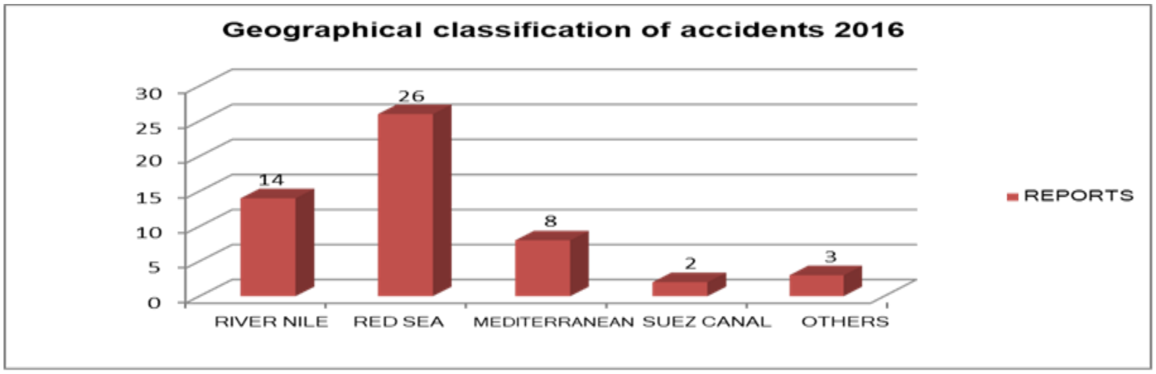
Predictor (standardized)	Standardized β	p-value	Interpretation (academic, non-causal)
Enforcement cases (X_2)	− 0.37	0.02	More enforcement activity is associated with lower spill outcomes, consistent with increased expected costs of non-compliance.
Reception capacity availability (X_3)	− 0.29	0.04	Greater reception-capacity availability is associated with lower spill outcomes, consistent with improved feasibility of compliant waste handling.

As shown in Table 3, higher inspection activity, stronger enforcement follow-through, and greater availability of reception facilities are each negatively associated with spill outcomes.
These findings are consistent with the interpretation that enforcement credibility and feasibility of enforcement are factors in the reduction of pollution incidents. The results are interpreted as being associational, rather than causal, in nature, recognizing the possibility of endogeneity and non-standard reporting practices. However, the consistency of the associations with temporal patterns and qualitative evidence improves their interpretive validity.

10.4 Spatial Distribution and Hotspot Dynamics

The kernel density analysis of spatial data reveals the existence of a fixed geographical pattern of oil spill incidents along the main operational routes, such as the Suez Canal and the approach areas to the ports. These areas are characterized by high ship density and complex operational patterns.
With time, the spill hotspot intensity becomes more fragmented and localized, suggesting a decrease in the number of major high-risk spill hotspots rather than the disappearance of spill risk. The geographical pattern of the spill hotspots at different times is shown in Figure 2.

Figure 2. Spatial distribution of oil-spill hotspots across Egyptian coastal/port areas (KDE surfaces, selected periods)



Source: Author based on data collected from Egyptian Environmental Affairs Agency.

Robustness checks confirm that these spatial patterns are stable across alternative GIS parameter settings, reinforcing their analytical reliability.

10.5 Institutional Mechanisms and Qualitative Evidence

Qualitative evidence from 25 semi-structured interviews provides insight into the institutional mechanisms underlying the quantitative and spatial findings as shown in table 4. Four recurring themes emerge: inter-agency coordination and role clarity, technical and human capacity constraints, legal consistency and enforcement credibility, and the role of information systems and monitoring technologies.

Table 4. Summary of thematic analysis of stakeholder interviews (N = 25)

Theme	Coding frequency (%)	Illustrative statement (anonymized)
Inter-agency coordination	32	"Overlapping inspection responsibilities can delay a unified response."
Technical & human capacity	26	"Regional units need more training and better real-time data tools."
Legal & enforcement consistency	23	"Stronger penalties improved deterrence, but consistency matters."
Technological modernisation	19	"Tracking and monitoring tools reduced undetected discharges."

Coding frequency (%) reflects the share of coded references across all interviews attributable to each theme (themes are not mutually exclusive; a single interview may contribute to multiple themes).

The respondents were consistent in pointing out that the initial implementation was hampered by overlapping responsibilities and fragmented workflows. The observed improvements after 2013 were attributed to better allocation of responsibilities, synchronization of inspection procedures, and improved access to vessel tracking and monitoring data.
The existing capacity and infrastructure deficits also help to explain the persistence of spill risk.

10.6 Integrated Interpretation and Triangulation

The convergent mixed-methods design allows for the combination of quantitative, spatial, and qualitative data through systematic triangulation. On all strands, the results point to a consistent pattern of change: spill outcomes are decreased in subsequent phases of implementation, enforcement-related conditions are associated with better outcomes, and the risk of spatial spill becomes less concentrated with time. Where there is divergence, this is due to the limitations of reporting, capacity differences, or localized operational constraints rather than a contradiction of the pattern. The evidence supports a mechanism-based interpretation in which MARPOL Annex I implementation is most effective when legal provisions, enforcement capacity, reception infrastructure, and information systems operate as an integrated chain.

11. Conclusion

This research examines the relationship between MARPOL Annex I compliant implementation in Egypt and recorded patterns of marine oil pollution outcomes from 1990 to 2023. Using a mixed-methods research design, this study combines national time-series evaluation, multivariate associations related to enforcement, geographic information system hotspot mapping in port and coastal regions, and qualitative evidence from semi-structured interviews with key implementing officials. By combining these approaches, this research seeks to enhance inference by connecting patterns of outcomes to likely mechanisms of enforcement and geographic operation, rather than focusing on a single body of data or research tradition.

Across the different bodies of evidence, the results suggest a pattern of improvement in oil spill outcomes in the latter stages of implementation compared to earlier stages. Descriptive time-series comparisons suggest a pattern of reduced spill outcomes in more contemporary stages of implementation, while the time-series reasoning supports an inference that changes in spill patterns are temporally associated with major implementation milestones.

The multivariate part of the analysis finds support for a mechanism-based interpretation, suggesting that enforcement-related factors, specifically the activity of inspections, the follow-through on enforcement, and the availability of reception facilities to facilitate compliant waste management, are each related to better spill outcomes. The geographic analysis provides a complement to the operational assessment by pointing to high-risk corridors and approaches to ports, suggesting that the effectiveness of implementation remains a concern in space despite improvements. The qualitative findings provide a holistic interpretation of the translation of legal and institutional provisions to operational success. The themes of the interviews suggest that progress is contingent upon mandates, technical capacity, human capacity, and information systems that can enable detection, verification of documentation, and subsequent action.

At the same time, there is recognition of the challenges that exist, such as the difficulties of coordination, disparities in capacity at different sites, and the requirements of high-traffic routes, which are typical in high-risk areas and suggest that the risk of spills may continue. the implications of the current study for policy and enforcement in Egypt are several. First, it is obvious that an integrated approach, which combines enforcement, infrastructure, and information, is necessary since the credibility of enforcement activities could be questioned if there is not a corresponding level of reception infrastructure and monitoring and reporting systems. Second, the hotspot method is a valuable tool for resource allocation since inspection and surveillance activities need to concentrate on high-risk roads and routes to ports, with periodic adjustment to reflect changes in traffic and infrastructure patterns.

Third, it is important to recognize that the importance of institutional coordination is an implementation consideration rather than a formality because the lack of coordinated mandates and different reporting systems could affect both deterrence and measurement.

Some limitations of the study are worth noting. Spill records could be prone to underreporting or changes in reporting patterns over time, and enforcement effort may react endogenously to perceived risk, making causal inference more complex. Nevertheless, the study chooses to view quantitative associations mainly as indicators of temporal coincidence and association, which are reinforced by spatial and qualitative mechanisms of triangulation. Future studies might improve causal inference by including measures of vessel traffic exposure, using quasi-experimental controls where appropriate (such as comparative corridors or ports with varying implementation intensity), and extending the spatial analysis with geocoding and exposure standardization.

In conclusion, there is evidence to support a mechanism-based inference that MARPOL Annex I-compliant implementation in Egypt is most likely to be related to better oil pollution outcomes when compliance is defined in terms of the integrated institutional roles, effective follow-up on inspection and enforcement, sufficient reception facilities, and information systems supporting targeted monitoring. Improving these interlocking elements, especially in areas of persistent high risk, provides a viable route to further mitigate marine oil pollution and to consolidate gains in regulation.

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Evaluating Maritime Crew Knowledge of Shipping-Related GHG Impacts on the Climate System's Equilibrium

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المستخلص

تهدف هذه الدراسة البحثية إلى تقييم معرفة الضباط والمهندسين البحريين بتأثير انبعاثات غازات الاحتباس الحراري في النقل البحري على توازن النظام المناخي.

تستخدم هذه الدراسة ثلاث طرق لتحليل بياناتها إحصائيًا، وهي اختبار مربع كاي، واختبار ويلكوكسون لعينة واحدة، واختبار فيشر- فريمان- هالتون الدقيق. واستُخدم الاستبيان كأداة رئيسية لجمع البيانات في هذه الدراسة. وشملت العينة ١٠١ ضابطًا ومهندسًا بحريًا.

تشير نتائج الدراسة إلى مدى معرفة المشاركين ووعيهم بأن النقل البحري يساهم بشكل كبير في انبعاثات غازات الاحتباس الحراري، والتي تلعب دورًا رئيسيًا في تغير المناخ.

توضح هذه الدراسة أهمية دمج قضية تغير المناخ في المناهج الدراسية البحرية لمختلف الأكاديميات البحرية، بالإضافة إلى التعاون بين مختلف الجهات المسؤولة، ممثلة بالحكومات والمنظمات الدولية وصناع القرار في المجال البحري، لتعزيز المشاركة المهنية والمجتمعية في التقنيات التي تساعد على الحد من الانبعاثات والتكيف مع تغير المناخ، الذي أصبح قضية دولية.

Abstract:

This research study aims to evaluate marine officers' and engineers' knowledge of the influence of greenhouse gas (GHG) emission in maritime shipping on the balance of the climate system.

This study uses three methods to statistically analyze the study data, which are the Chi-Square Test, the Wilcoxon One-Sample Test, and the Fisher-Freeman-Halton Exact Test. A questionnaire was used as the main method of data collection in this investigation. The sample was available with 101 marine officers and engineers.

The study results indicate the extent of knowledge and awareness among participants that maritime transport contributes significantly to greenhouse gas emissions, which play a major role in climate change.

This study clarifies the importance of integrating the issue of climate change into the maritime curricula of various maritime academies. in addition to cooperation between the various

responsible parties, represented by governments, international organizations, and decision-makers in the maritime field, to promote professional and societal participation in technologies that help mitigate emissions and adapt to climate change, which has become an international issue.

Keywords: Climate system, Greenhouse gas, Maritime shipping, Marine officers and engineers

1. Introduction:

The amount of (GHGs) in the atmosphere has been greatly increased by human activities since around 1750, which has led to an increase in temperature over the last few hundred years. The mean surface air temperature has increased by 1.1°C over pre-industrial levels, indicating that global warming has intensified in recent decades. (GHGs) and other pollutants, such as particulate matter (PM) and ozone precursors (O_3), are released during the extraction and burning of fossil fuels. (Wang et al., 2023)

One of these is maritime shipping, which is the main means of transportation for manufactured goods, food, and raw materials. Transcontinental trade is also facilitated by it. Over 80% of goods traded globally and 70% of the value of international trade are transported by ships of various kinds. (Salihoglu & Bal Besikci, 2021). However, shipping is also a major source of (GHG) emissions, making up two to three percent of global CO_2 emissions. (Bullock et al., 2022; Roy and Chakraborty, 2025).

The purpose of this section is to examine and assess how the emission of (GHGs) in maritime shipping affects the climate system's equilibrium and the International Maritime Organization's response. This is accomplished by means of earlier research.

The primary long-lived greenhouse gases, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), and carbon tetrachloride (CCl_4), are all increasing in the atmosphere because of human activities. (Watson et al., n.d.)

The extraction and burning of fossil fuels, as well as changes in land use and the use of halocarbons, are the main ways that humans have seriously disrupted the climate system's energy balance. Methane and nitrous oxide, two potent (GHGs), are also released into the environment by waste treatment and agriculture. (Bruhwiler et al., 2021)

The expansion of economies and populations is a major contributing factor to the rising worldwide demand for energy. They have helped both the overall number of ships engaged in international shipping and the notable expansion of international maritime trade. (Islam Rony et al., 2023) Due to an 18% increase in global trade between 2016 and 2019, shipping fuel consumption rose by 50% between 2012 and 2040. (Lin & Raza, 2020)

Shipping now accounts for 2.89% of global anthropogenic emissions due to industry's reliance on fossil fuels. Ship emissions of greenhouse gases, including sulfur oxides, nitrogen oxides, and particulate matter, pose a major threat to human health and the environment within 400 kilometers of land. (Elashwah 2025 & Ampah et al., 2021)

The shipping industry has several detrimental effects on the marine environment. A few factors contribute to climate change, such as the atmospheric release of greenhouse gases like CO_2 and short-lived climate pollutants like methane and black carbon, NO_x, and SO_x in different marine locations. (Eyring et al., 2010)

The ports sector is one of the maritime sites; port activities are essential to the growth of the economies and job markets of developing countries. (Azarkamand etal. 2020) Because of their complexity and diversity, this industry's operations have a negative impact on the environment. Waste creation, soil contamination, noise pollution, and gas emissions that lead to air pollution are some of the effects. (Diniz et al., 2023)

Port operations are one facet of marine activity; green ports, also known as sustainable ports, are those that

use less energy and produce fewer emissions. (KSIĄŻKIEWICZ, 2020) This can be accomplished with the aid of energy-efficient devices and renewable energy sources like solar or wind power. (Inal, 2023)

Climate change is a danger because of the potential problems it may cause in the future. Climate change may have several detrimental repercussions. The earth's climate is currently changing in a few ways and at a very rapid pace. (Edward 2020)

For instance, there are numerous indications of climate change. (Fahad, 2020):

1- Consequences of the Arctic Ice Crisis: Temperature increases brought on by an increase in greenhouse gases may have detrimental consequences on the environment. The Arctic ice has been melting as a result.

2- Oceanic Impacts: The effects of climate change on the ocean are also noticeable. Large volumes of CO_2 are trapped in oceans, which act as significant "carbon pools," preventing them from entering the upper atmosphere. Rising ocean temperatures and more acidic waters because of increased CO_2 concentrations are already influencing the oceans. At a temperature of 1°C, the consequences of climate change are already causing considerable changes in the oceans, with a critical threshold of 1.5°C and higher predicted. Coral reefs are expected to decrease by 70–90% at 1.5°C. A 2℃ increase in temperature will cause practically all coral reefs to disappear. It is devastating for more than just the fauna because coral reef fish are the main source of protein for half a billion people.

3- More than other places, polar regions are seeing the consequences of climate change. The northern and southern hemispheres, which are also especially vulnerable to the consequences of global warming, play a major role in regulating the temperature of our planet.

4- Effects on the Pattern Changes in Precipitation: hurricanes, floods, droughts, and precipitation have all become more common during the last 20 years. While some areas receive a lot of precipitation, others endure year-round drought.

The current study employs a questionnaire as part of its approach to increased awareness and knowledge of the impact of (GHG) emissions from maritime shipping on the balance of the climate system.

2. Methods of Analysis:

The knowledge of marine officers and engineers working on commercial ships regarding the effects of (GHG) emissions in maritime shipping on the climate system's equilibrium was the focus of the research problem. The selected methodological approach might be considered a methodical and scientific approach to the research topic. This method makes it easier to incorporate research results into the topic's larger theoretical and methodological framework. (Kothari, 2004)

The features of the research questions and the topic being studied are the main factors that influence the choice of research methodology. As suggested by Denzin and Lincoln (2005), This research paper attempts to provide participants with a comprehensive overview of their views and knowledge about greenhouse gases, including their sources, their impact on climate balance, and strategies for mitigating and adapting to this global phenomenon. It is based on data gathered from maritime professionals at both the managerial and operational levels, with varying degrees of experience. Descriptive statistics and suitable inferential tests are used for this.

2.1 Questionnaires Design:

The questionnaire was designed as a research tool to evaluate knowledge of the impact of greenhouse gases on the Earth's climate system through several participants working in the maritime sector on various commercial ships.

The questionnaire was multidimensional; each item was examined separately rather than as a single composite scale. Consequently, internal consistency reliability measures such as Cronbach's alpha were not deemed appropriate. Instead, the analysis relied on descriptive statistics and suitable inferential tests to examine differences and associations among variables.

The questionnaire was revised several times to make sure it followed pilot study rules, reviewed data, filled out options, and utilized appropriate language and vocabulary, to ensure the accuracy and security of the survey questions' wording and scientific design, as well as the extent to which the problem and objectives of the study have been handled. Along with the review by industry experts, additional phrases were added, and some were recast to improve the study tool and the use of the five-level Likert scale.

The researcher distributed hard copies of the questionnaires to those who are on vacation to renew their certificates at the Arab Academy for Science, Technology, and Maritime Transport, and the Google Drive link was sent directly to officers and engineers via social media, totaling 101 people.

2.2 Sampling Procedure:
The researchers were able to select marine officers and engineers from the Arab Academy for Science, Technology, and Maritime Transport who had experience sailing on a variety of ships by using stratified sampling.

Every questionnaire that was returned was examined to make sure it was legitimate and free of stray signs and other damage. After receiving 101 accurate questionnaires, the information was input into an Excel spreadsheet.

2.3 Data Collection:
A standardized questionnaire was employed to gather the data. The previously described tool was specifically designed to collect information about the demographic characteristics of the respondents and their awareness of the impact of (GHG) emissions.

All information collected is confidential and will not be shared except with the permission of the participants or as required by law.

2.4 Research Limitations:
Any scientific research has limitations that can prevent generalization of the results. This research faced a limitation regarding the place, as this research targeted the officers and engineers in Egypt. The researcher suggests conducting future studies of different nationalities too if the same results are achieved.

2.5 Data Analysis:
The data that was gathered underwent analysis through the utilization of the Statistical Package for the Social Sciences (SPSS), specifically version 27. The following analytical techniques were used:

- The sample was described, and participants' opinions were summarized using descriptive statistics: frequencies, percentages, means, medians, and standard deviations.
- For ordinal-scale items, the Wilcoxon One-Sample Test was used to determine whether respondents' perceptions deviated considerably from a postulated reference value.
- For categorical variables with tiny, predicted cell counts, the Fisher-Freeman-Halton Exact Test was utilized to investigate variations in answers based on years of maritime sector experience.
- When test assumptions were satisfied, the Pearson Chi-Square Test was used to evaluate relationships between categorical variables and years of marine experience.
- The data were displayed in tables and figures for interpretation, and all statistical tests were performed at a significant level of $p < 0.05$.

3. Results:

3.1 Analysis of Questionnaire Results:

3.1.1 General awareness:

3.1.1.1 Awareness of the Concept of (GHGs):

The study sample's answers on their knowledge with the phrase (GHGs) are displayed in Table 1. using the Wilcoxon one-sample test results and descriptive statistics.

Table (1) Awareness of the Concept of Greenhouse Gases

Are you familiar with the term greenhouse gases (GHGs)?	Frequency	Percent	Mean ± SD	Median	Wilcoxon One-Sample Test	
					Standardized Test Statistic	Sig.
Very familiar	28	27.72%	3.52± 1.23	4	3.805	0.000
Familiar	23	22.77%				
Somewhat familiar	31	30.69%				
Not very familiar	11	10.89%				
Not familiar at all	8	7.92%				
Total	101	100.00%				

Table (1) shows the results of the Wilcoxon one-sample test, indicating that the observed degree of familiarity and the anticipated neutral or reference value differ significantly. that rather than being random or marginal, the respondents' understanding of greenhouse gases is significant and statistically significant.

Overall, the research sample's comprehension of greenhouse gases is adequate, offering a solid foundation for examining their awareness of how they affect the climate system.

3.1.1.2 Identification of Greenhouse Gases:

Table (2) shows results of study sample responses about gases that are considered greenhouse gases, with the results of the Fisher–Freeman–Halton exact test.

Table (2) Identification of Greenhouse Gases

Which of the following gases do you think are greenhouse gases? (n=28)	Years in the Maritime Industry			Total	Rank	Fisher-Freeman-Halton Exact Test	
	Less than 5 years	5-10 years (n=37)	More than 10 years (n=36)			Test Statistic	Sig.
Count	16	24	22	62			
Carbon dioxide (CO_2)					1	0.44	0.81
%	57.14%	64.86%	61.11%	61.39%			

Which of the following gases do you think are greenhouse gases? (n=28)		Years in the Maritime Industry			Total	Rank	Fisher-Freeman-Halton Exact Test	
		Less than 5 years	5-10 years (n=37)	More than 10 years (n=36)			Test Statistic	Sig.
Methane (CH4)	Count	10	10	14	34			
						2	1.25	0.58
	%	35.71%	27.03%	38.89%	33.66%			
Oxygen (O2)	Count	3	3	6	12	5	1.29	0.55
	%	10.71%	8.11%	16.67%	11.88%			
Ozone (O3)	Count	1	3	10	14	4	8.33	0.01
	%	3.57%	8.11%	27.78%	13.86%			
Water vapor (H2O)	Count	7	5	5	17			
						3	1.78	0.40
	%	25.00%	13.51%	13.89%	16.83%			

The results in table (2) indicate that awareness of carbon dioxide as a greenhouse gas is relatively high and consistent across years of experience in the marine field, while knowledge of other gases remains limited.

3.1.1.3 The perceived gravity of increasing greenhouse gas concentrations and their effects on the planet's climate system:

Table (3) shows results of study sample responses regarding the dangers of rising greenhouse gas concentrations and their impact on the climate, according to years of experience, using the Pearson chi-square test to examine group differences.

Table (3) The perceived gravity of increasing greenhouse gas concentrations

How serious do you think the problem of rising greenhouse gas concentrations is for Earth's climate system?		Years in the Maritime Industry			Total	Pearson Chi-Square Test	
		Less than 5 years (n=28)	5-10 years (n=37)	More than 10 years (n=36)		Test Statistic	Sig.
Extremely serious	Count	14	7	13	34	8.17	0.09
	%	50.00%	18.92%	36.11%	33.66%		
Moderately serious	Count	13	25	18	56		
	%	46.43%	67.57%	50.00%	55.45%		

How serious do you think the problem of rising greenhouse gas concentrations is for Earth's climate system?		Years in the Maritime Industry			Total	Pearson Chi-Square Test	
		Less than 5 years (n=28)	5-10 years (n=37)	More than 10 years (n=36)		Test Statistic	Sig.
Not serious	Count	1	5	5	11		
	%	3.57%	13.51%	13.89%	10.89%		

The results indicate that most respondents across all experience groups perceive the problem as either moderately serious or extremely serious. Despite these descriptive variations, the Pearson chi-square test indicates that the association between years of maritime experience and perceived seriousness is not statistically significant ($\chi^2 = 8.17$, $p = 0.09$). Accordingly, differences in perceptions across experience groups do not reach the conventional level of statistical significance.

Overall, the findings suggest a broadly shared recognition among maritime professionals of the seriousness of rising greenhouse gas concentrations and their potential impact on the Earth's climate system, irrespective of years of experience in the industry.

3.1.2 Causes and Sources:

3.1.2.1 Perceptions of Major Sectoral Contributors to Greenhouse Gas Emissions by Years of Maritime Experience:

Table (4) presents respondents' perceptions of the sectors that contribute most to greenhouse gas emissions, disaggregated by years of experience in the maritime industry, along with the results of the Fisher–Freeman–Halton exact test.

Table (4) Sectoral Contributors to Greenhouse Gas Emissions

Which sectors contribute most to greenhouse gas emissions?		Years in the Maritime Industry			Total	Rank	Fisher-Freeman-Halton Exact Test	
		Less than 5 years (n=28)	5-10 years (n=37)	More than 10 years (n=36)			Test Statistic	Sig.
Maritime industry	Count	12	11	18	41	1	3.19	0.20
	%	42.86%	29.73%	50.00%	40.59%			
Energy production	Count	10	4	11	25	3	6.63	0.04
	%	35.71%	10.81%	30.56%	24.75%			
Industry and manufacturing in general	Count	10	16	15	41	1	0.42	0.85
	%	35.71%	43.24%	41.67%	40.59%			

Which sectors contribute most to greenhouse gas emissions?		Years in the Maritime Industry			Total	Rank	Fisher-Freeman-Halton Exact Test	
		Less than 5 years (n=28)	5-10 years (n=37)	More than 10 years (n=36)			Test Statistic	Sig.
Deforestation/land use change	Count	5	17	9	31	2	6.46	0.04
	%	17.86%	45.95%	25.00%	30.69%			

The findings show that the maritime industry and manufacturing in general are jointly ranked as the most frequently identified contributors.

Overall, these results reveal both commonalities and experience-related differences in perceptions of sectoral greenhouse gas contributors. While industry, manufacturing, and maritime activities are widely recognized as significant sources of emissions, awareness of the roles played by energy production and deforestation varies significantly with years of maritime experience.

3.1.2.2 Perceptions of Human Activities as the Primary Driver of Increased Greenhouse Gas Concentrations:

Table (5) presents respondents' views on whether human activities are the main cause of increased greenhouse gas concentrations, along with descriptive statistics and the results of the Wilcoxon one-sample test.

Table (5) Perceived role of human activities in Greenhouse Gas

Do you think human activities are the main cause of increased GHG concentrations?	Frequency	Percent	Mean ± SD	Median	Wilcoxon One-Sample Test	
					Standardized Test Statistic	Sig.
Extremely relevant	15	14.85%				
Very relevant	18	17.82%				
Somewhat relevant	45	44.55%				
			3.18± 1.09	3	1.687	0.092
Slightly relevant	16	15.84%				
Not relevant at all	7	6.93%				
Total	101	100.00%				

The results indicate a moderate level of agreement with the anthropogenic explanation of rising greenhouse gas concentrations. The overall mean score of 3.18 ± 1.09, with a median value of 3, suggests a central tendency toward a moderate level of agreement rather than strong conviction.

Overall, the results here indicate that although most participants agreed that human activity plays an influential role in increasing greenhouse gas concentrations, some still believe that this is not the strongest reason.

3.1.3 Effects on the climate system:

3.1.3.1 Perceived Effects of Climate Change Linked to Increased Greenhouse Gas Levels:

Table (6) The results of the study sample's responses regarding the most prominent negative effects of increased greenhouse gas levels are categorized according to the participants' years of experience. with the results of the Fisher–Freeman–Halton exact test.

Table (6) Climate Change associated with higher Greenhouse Gas levels

Which climate change do you associate with higher GHG levels?		Years in the Maritime Industry			Total	Rank	Fisher-Freeman-Halton Exact Test	
		Less than 5 years (n=28)	5-10 years (n=37)	More than 10 years (n=36)			Test Statistic	Sig.
Global temperature rise	Count	19	21	13	53	1	6.71	0.03
	%	67.86%	56.76%	36.11%	52.48%			
Melting glaciers and polar ice caps	Count	10	10	13	33	3	1.00	0.64
	%	35.71%	27.03%	37.14%	33.00%			
Sea level rise	Count	14	13	20	47	2	3.23	0.20
	%	50.00%	35.14%	55.56%	46.53%			
Ocean acidification	Count	3	2	11	16	4	8.66	0.01
	%	10.71%	5.41%	30.56%	15.84%			
Changes in rainfall patterns	Count	5	2	3	10	5	2.68	0.26
	%	17.86%	5.41%	8.33%	9.90%			

The findings indicate that global temperature rise is the most frequently associated climate change. Overall, the results suggest that respondents most readily associate higher greenhouse gas levels with more visible and widely publicized climate impacts, such as global temperature rise and sea level rise. In contrast, more complex or indirect consequences, particularly ocean acidification and altered rainfall patterns, are less frequently recognized, with significant differences emerging only among more experienced maritime professionals.

3.1.3.2 The direct effect of greenhouse gas emissions on the climate system's stability:

Table (7) Results of the study sample's responses regarding participants' opinions that greenhouse gases affect climate balance, according to years of experience using the Pearson chi-square test.

Table (7) The direct effect of greenhouse gas emissions on the climate system's

How much do you agree with the statement: Greenhouse gas emissions have a direct impact on the stability of Earth’s climate system.		Years in the Maritime Industry			Total	Pearson Chi-Square Test	
		Less than 5 years (n=28)	5-10 years (n=37)	More than 10 years (n=36)		Test Statistic	Sig.
Strongly agree	Count	7	11	8	26	8.46	0.39
	%	25.00%	29.73%	22.22%	25.74%		
Agree	Count	9	15	6	30		
	%	32.14%	40.54%	16.67%	29.70%		
Neutral	Count	7	7	13	27		
	%	25.00%	18.92%	36.11%	26.73%		
Disagree	Count	4	3	6	13		
	%	14.29%	8.11%	16.67%	12.87%		
Strongly disagree	Count	1	1	3	5		
	%	3.57%	2.70%	8.33%	4.95%		

The results indicate a general trend among marine officers and engineers to agree on this noticeable effect of these gases. Despite these descriptive differences, the Pearson chi-square test indicates that the association between years of maritime experience and agreement with the statement is not statistically significant ($\chi^2 = 8.46$, $p = 0.39$).

Overall, the results show that there is an understanding, knowledge, and awareness of the relationship between greenhouse gases, of which the marine industry is one source, and climate change.

3.1.4 Adaptation and mitigation:

3.1.4.1 Perceived Efficiency of Greenhouse Gas Emission Reduction Measures:

Table (8) The results show the most effective measures to reduce greenhouse gas emissions. with the results of the Fisher–Freeman–Halton exact test.

Table (8) Actions to reduce Greenhouse Gas emission

Which actions do believe are most effective in reducing greenhouse gas emissions?		Years in the Maritime Industry			Total	Rank	Fisher-Freeman-Halton Exact Test	
		Less than 5 year (n=28)	5 : 10 years (n= 37)	More than 10 years (n=36)			Test Statistic	Sig.
Switching to renewable energy	Count	14	21	24	59	1	1.87	0.39
	%	50.00%	56.76%	66.67%	58.42%			

Which actions do believe are most effective in reducing greenhouse gas emissions?		Years in the Maritime Industry			Total	Rank	Fisher-Freeman-Halton Exact Test	
		Less than 5 year (n=28)	5 : 10 years (n= 37)	More than 10 years (n=36)			Test Statistic	Sig.
Improving energy efficiency	Count	13	5	6	24	3	10.03	0.01
	%	46.43%	13.51%	16.67%	23.76%			
Promoting public transportation	Count	4	6	12	22	4	4.07	0.14
	%	14.29%	16.22%	33.33%	21.78%			
Reforestation and forest conservation	Count	7	1	4	12	5	7.20	0.02
	%	25.00%	2.70%	11.11%	11.88%			
Reducing waste and promoting recycling	Count	8	7	11	26	2	1.51	0.49
	%	28.57%	18.92%	30.56%	25.74%			

The survey results indicate that many participants with varying years of experience believe that relying on renewable energy is the most effective measure for mitigating or adapting to climate change. However, another group holds a different view, promoting public transportation, reforestation, and forest conservation and promoting recycling, reflecting differences in priorities.

3.1.4.2 The parties responsible for taking the lead in addressing the phenomenon of greenhouse gas emissions:

Table (9) shows the participants' views on the entities responsible for adopting a set of strict measures to reduce these emissions, with the results of the Fisher–Freeman–Halton exact test.

Table (9) Responsibility for leading GHG mitigation efforts

In your opinion, who should take the lead in addressing greenhouse gas emission?		Years in the Maritime Industry			Total	Rank	Fisher-Freeman-Halton Exact Test	
		Less than 5 years (n=28)	5-10 years (n=37)	More than 10 years (n=36)			Test Statistic	Sig.
Governments	Count	16	19	11	46	2	5.27	0.07
	%	57.14%	51.35%	30.56%	45.54%			
International organizations (eg, UN)	Count	15	13	24	52	1	7.28	0.03
	%	53.57%	35.14%	66.67%	51.49%			
Businesses / industries	Count	8	9	10	27	3	0.24	0.92
	%	28.57%	24.32%	27.78%	26.73%			
Educational institutions	Count	6	0	7	13	4	10.51	0.00
	%	21.43%	0.00%	19.44%	12.87%			

In general, the participants were Marine officers and engineers, and therefore the prevailing view was that the responsibility lay with international organizations (e.g., the UN).

4- Discussion:

The main question of research is whether there is knowledge of the impact of greenhouse gases on climate systems. After analyzing the results, it can be concluded that, as in other similar studies (Eyring et al., 2010), (Azarkamand etal. 2020) and (Diniz et al., 2023) rising greenhouse gas concentrations and their potential impact on the Earth’s climate remain a major concern.

The maritime shipping sector is viewed as a contributor to greenhouse gas emissions, and one of the points that must be emphasized, and which the results showed, is that knowledge of these gases and also their direct impact on the climate system is high, but there is a disparity in the level of awareness of the sources of these gases and understanding of their repercussions.

Although many of the observed differences were not statistically significant, the results confirm the close relationship between the years of experience of the sailors participating in the survey and their awareness of the effects of these gases, as knowledge increases with experience.

In view of the overall results, shipping decision-makers should consider the importance of increasing attention to educating maritime officers in the shipping sector about these gases and the plans of the International Maritime Organization and other bodies, such as national governments, to mitigate and adapt to reduce the resulting effects.

The above suggestions aim to close known gaps in knowledge and create a climate that supports proactive behavior and policymaking that recognizes the urgent need to reduce these emissions.

One of the main limitations of the study is the research faced a limitation regarding the place, as this research targeted the officers and engineers in Egypt. As a result, it would be ideal to increase the sample size to include individuals of other nationalities.

5. Conclusion and Recommendations:

The results obtained in this study can be relied upon to assess the extent of knowledge about the impact of greenhouse gases resulting from the marine industry on the balance of the climate system.

This study recommends cooperation between governments, shipping companies, and international organizations, as well as increased funding for scientific research related to technologies for reducing these emissions.

Also, reviewing the environmental policies issued by the International Maritime Organization and encouraging the use of renewable energy on board ships and in ports to become green ports.

the necessity of focused environmental education and training for the maritime sector, with a stronger focus on the entire range of greenhouse gases and how each contributes to climate change.

The researcher recommends doing further research on other nations from various maritime colleges and institutes to determine whether the same outcomes would be obtained, as this study was limited to Egypt.

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Assessing the Impact of Automating the Operational Processes on Enhancing the Efficiency and the Competitiveness of Khalifa Port

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المستخلص

تهدف هذه الدراسة إلى تقييم أثر أتمتة العمليات التشغيلية على تعزيز الكفاءة التشغيلية والقدرة التنافسية في ميناء خليفة، من خلال تبني منظور تحليلي متكامل يجمع بين الأبعاد الاستراتيجية والتشغيلية والتجارية والخدمية. اعتمدت الدراسة على منهج نوعي قائم على مقابلات متعمقة مع قيادات إدارية متعددة المستويات داخل الميناء، شملت الإدارة العليا، والتطوير الاستراتيجي، وإدارة المشاريع، وتطوير الأعمال، وخدمة العملاء، والشؤون التجارية، بهدف استكشاف تصوراتهم حول دور الأتمتة في تحسين الأداء المؤسسي. أظهرت النتائج وجود توافق عام على أن الأتمتة تسهم في زيادة إنتاجية العمليات، وتقليل زمن الدورة التشغيلية، وتحسين استغلال الموارد، وخفض التكاليف التشغيلية، إضافة إلى تعزيز موثوقية الخدمة وتجربة العملاء. كما أوضحت النتائج أن القيمة الاستراتيجية للأتمتة تتمثل في دعم اتخاذ القرار القائم على البيانات، وتعزيز مرونة الميناء في مواجهة الاضطرابات، وتقوية موقعه التنافسي في السوق العالمي. وفي المقابل، حددت الدراسة مجموعة من التحديات المرتبطة بتكامل الأنظمة، وإدارة التغيير، وتأهيل الكوادر البشرية، مؤكدةً أن نجاح الأتمتة لا يعتمد على التكنولوجيا فقط، بل على جاهزية البيئة التنظيمية كذلك. وتسهم الدراسة في سد فجوة في الأدبيات من خلال تقديم تحليل متعدد الأبعاد يربط بين تطبيقات الأتمتة ونتائجها المؤسسية، وتوفير إطار تفسيري يمكن أن يدعم الدراسات المستقبلية حول الموانئ الذكية والتنافسية المستدامة.

الكلمات المفتاحية :الأتمتة، العمليات التشغيلية، الكفاءة، التنافسية، ميناء خليفة.

Abstract:

This study sets out to examine the effects of automation of operational process streams on operational efficiency and competitiveness improvement at Khalifa Port using a strategy, operations, commerce and service integration analytical framework. The study uses a qualitative methodology to geopolitically capture the perceptions of Digital Transformation (DT) and automation of operational process streams to enhance institutional performance through the lens of the Port employees strategically positioned at the apex of the organization and at the levels of strategy, project management, business development, customer service and commerce. The study establishes a near consensus on DT and operational process automation as key to enhancing operational efficiency, including, but not limited to, increased operational productivity, reduced operational cycle times, and improved resource productivity vis-a-vis unit operational cost reduction, increased service reliability and enhanced customer service experience. The study establishes automation's shift of the Port's operational strategy through the improvement of the Port's capabilities on data driven decision making, increased place/space resilience in the face of disruptive change, and in the improvement of the Port's competitiveness and operational efficiency on the global market. The study also identifies the challenges of system integration, change management, and the upskilling of the workforce, to underscore that the successful operationalization of automation is more than a technological solution within a system, but is also a function of the organization's posture. The research helps address a gap in the literature by providing a multifaceted analysis of the connections between the outcomes of automation applications and institutions, as well as offering explanatory principles that may direct future research on smart ports and sustainable competitiveness.

Keywords: Automation, Operational Processes, Efficiency, Competitiveness, Khalifa Port.

1. Introduction:

Khalifa Port, located between Abu Dhabi and Dubai, is one of the world's most technologically advanced ports. Its deep-water facilities allow the port to act as a major gateway for the world's shipping lines. It has fully automated container terminals and modern logistics, as a result, its infrastructure can support operational efficiency and competitiveness. This strengthens its role as a vital hub for maritime and trade activities while contributing significantly to the UAE's economic growth and global trade connectivity.

In a larger context, the international maritime industry is a crucial element of economic activity and trade, given the role of shipping lines and seaports in the global supply chain by providing the means for cross-border trade. In a given port, the efficiency of its spatial organization is especially critical, as it defines the velocity at which vessels are loaded and unloaded, as well as the various ways in which cargo is moved and stored around the port. Ports which are technically advanced can provide faster and more extensive service to vessels at more economical rates than the shippers and carriers. Conversely, ports which are technically inefficient are subject to more frequent congestion and higher operational costs which reduce their competitiveness in international trade (Elgazzar and Ismail, 2021).

Miller and Hyodo (2022), describe technical efficiency in container terminals as achieving a relationship between productivity and the optimal allocation of resources, such as maximized facility utilization, the optimal assignment of labor, minimal queuing, and heightened rates of flow control to maximize throughput.

Improving technical efficiency of ports enhances global supply chain systems as it positively impacts the logistics time and costs, which are critical for international trade. That is, a port is efficient when it reduces the time required to process cargo, thereby streamlining the volume of trade. Furthermore, it boosts output and lowers the level of expenditure on resources, which translates to reduced costs for the consumer (Baştuğ, 2023).

The rapid development and expansion of container shipping means that the demand for improved technical efficiency within the ports will continue to grow. Such ports that implement modern practices and technologies will be able to better satisfy customer demands and sustain their competitive edge. Therefore, the need to focus on technical efficiency becomes a modern day challenge to accommodate the increasing demands within a highly competitive global trade environment (Caldas et al., 2024).

2. Statement of the problem:

Ports have always been important for the movement of traded goods between countries. Khalifa Port is one of these important ports, but the competition is always changing, requiring the port to improve operational effectiveness and productivity. Khalifa Port has solid infrastructure and a good location, but that does not guarantee a competitive edge, and new strategies will be needed for the port to achieve this. Therefore, this study primarily concerns the automation of Khalifa Port to improve operational efficiency and competitive positioning, as well as any obstacles that may be present.

3. Literature review:

The last several years have seen considerable growth in research literature focused on the port sector's operational process automation. While the initial focus was on the purely technical aspects of process automation, more recently, the literature has begun to view process automation from an integrated institutional change perspective of process automation whereby institutional change affects operational efficiency and competitiveness. Brunila et al. (2021) highlighted that, from the perspective of digital transformation, the primary challenges in the port sector are not technologically driven, but rather, stems from the lack of integration of systems and restricted data sharing and interoperability among the stakeholders in the port community, which limits the automation's value. This is consistent with the findings of Henríquez et al. (2022) who, in a case study of the Port of Barcelona, pointed out that the technologies of Industry 4.0, in the absence of a port business model and service framework and operational relationship restructuring, are of little value. The technologies, in that case, may only serve as standalone technical solutions. When it comes to the quantitative element, the effect of automation on operational efficiency, with the help of analytical models, has been examined in a variety of studies.

As an example, Yen et al. (2023) used a DEA-Tobit model to determine the impact of “smart port” features on the operational efficiency of the world’s leading ports. He found that digital analytics and automation, to a considerable extent, leads to operational efficiency and decreased processing times, but the extent of the effect is predominantly a function of the digital framework and operational process interlinkage (Rafaat & Elsmsar, 2025). In the same vein, Tsagkaris & Moschovou (2025) posit that automation is not synonymous with improved operational performance unless complemented with the evolution of the people and process skills. Analogously, Nguyen & Pham (2025) proved that there is a strong positive correlation with the level of digital transformation, operational efficiency, and market share, and in doing so, they extended the relationship of automation to port's operational competitive advantage. Studies at a more specific operational level have examined the scheduling and coordination of automated systems at container terminals, as these are among the most operational cycle time.

For instance, Hu et al. (2025) showed that 'smart' coordination of quay cranes and automated guided vehicles (AGVs) diminishes completion time and enhances productivity. This was furthered by Zhou et al. (2023) through integrated optimization models for the scheduling of yard cranes and automated vehicles, which was cost-efficient and flowing better in storage yard operations. Furthermore, Yang & Hsieh (2024) illustrated that automation, as a technological investment, worked best in a comprehensive operational framework encompassing planning, coordination, and performance management.

Other studies analyzed automation from the perspectives of enhanced customer experience and service reliability within the service and supply chains. From this standpoint, smart gates may be exemplary. They help lessen operational bottlenecks, enhance the flow of and access to data, and facilitate transparency, which, as noted, positively impacts customer satisfaction (Basulo-Ribeiro et al., 2024). Improving the reliability of equipment and decreasing the frequency of equipment breakdowns (Garmouch et al., 2025) positively impacts the operational and commercial competitiveness of a port by increasing its capacity and improving adherence to schedules, which is a commercial concern. Collectively, the studies point to the fact that the port industry is strategically redefining the operational, service, and financial value of automation.

Although there are more smart port technologies, there are still more gaps in research because there are hardly any applied, integrated studies that include operational automation and its total institutional ramifications on efficiency and competitiveness, especially in the Middle Eastern tech ports like Khalifa port. Most studies tend to look either one way, either the more or not the automation side. Not operational singular performances. Most studies have frameworks, but are not operational or strategic, and more commercially or service integrated. Also, there are no studies that are more qualitatively focused that look more holistically and more at the middle management continuum and automate perspectives of executive leadership and the challenges of automation more than the digital transformation in ports. Also, the more focused simply to more automation, the more focused simply to more automation, not the more focused simply to more automation, not the more focused simply to more automation.

Consequently, this study aims to address this gap by offering a multidimensional perspective, grounded in detailed interviews, that connects automation applications with respective functional and strategic outcomes, thus enhancing the understanding of the positive impact of automation on operational efficiency and competitiveness in smart ports.

The originality of this study lays in developing an integrated analytical framework establishing the relationship between operational automation in ports and the multidimensional institutional impact of automation on operational and competitive efficiency from strategic, operational, commercial, and service perspectives. This functional variety provided a better balance of perspectives and organizational levels of how and what automation is evaluated, helping to fill the literature void, which is predominantly descriptive with a focus on technical or discrete operational parameters. The study also scientifically interprets using a qualitative framework the impact of organizational changes caused by the digital transformation of ports and the intersection of automation with the contemporary digital transformation of ports and the intersection of automation with contemporary sustainable competitive advantage, supply chain resilience, customer experience, and financial sustainability. This also contributes to the development of more pragmatic theoretical frameworks to assess the impact of automation in smart port settings.

4. Research importance:

- **Scientific Importance:**

The title's articulation of the construction of operational processes through the automation of activities in seaports and its relationship with operational efficiency and competitiveness is of utmost importance scientifically, as this is still in need of more substantive applied research, especially concerning the high-tech ports in the Middle East. In this regard, research on Khalifa Port is a unique and distinct empirical case that has the potential to enrich the domain of port management, supply chain management, and smart logistics by integrating the construction of technology with 'real' performance, as opposed to performative technology. Furthermore, the use of interviews as the main qualitative data collection tool, in addition to the quantitative data that will be derived from the surveys, will provide important organizational, human, and operational frameworks to address the influence of automation in the operational processes from the perspectives of the managers and the operators. This will enhance the explanatory power of the framework while informing the research and performance metrics in smart ports.

- **Practical Importance:**

The practical significance of this study is that it can assist port authorities and decision makers calculate their actual return on investment with respect to operational automation—what is actionable and, in this case, manageable. The study can assist in decision making relating to the expansion and/or the upgrading of automation systems within the port by providing evidence to justify such systems and/or their upgraded versions when operational automation is first assessed in relation to its impact on container handling speed, reduction of waiting time, productivity of equipment, operational cost, and overall efficiency. The study also offers insights and how future phases of implementation can be improved by relating challenges such as the need for training, change resistance, and difficulties of system integration to the challenges of automation upstream of such practices, thereby addressing the challenges of automation. As a result, the study is able to formulate operational strategies that enhance the competitive advantage of the port within the global marketplace and facilitate a sustainable and reliable improvement of performance in a highly competitive environment in the transport sector of the maritime industry.

5. Research methodology:

This research seeks to identify the implications of automating operational activities for improvements in efficiency and competitiveness in the study of relevant ports. Furthermore, to examine container terminals in the study and draw a conclusion regarding the efficiencies and operational inefficiencies at port(s) under study, and to provide recommendations to eliminate said inefficiencies and improve the relevant competitive efficiencies of the ports in question. Thus, this study adheres to a deductive "quantitative" framework. A single interview with each of the relevant constituents, port operator, manager, and tech provider, have been conducted. The interview serves the purpose of obtaining relevant information regarding the extent of operational automation at present, the extent to which operational automation serves to increase efficiency and competitiveness of the relevant ports, and the obstacles to automation, if any. The information collected will be vital to the development of recommendations for automation of operational processes of ports and for enhancing the competitive efficiencies of the ports in relation to the global competitive landscape.

Seven questions were generated by the researcher to identify the impact of automation at Khalifa Port. Furthermore, like other ports, to examine and provide a description of the impact of automation on the efficiency and competitiveness of Khalifa Port. The questions are as follows:

Table 1. proposed questions

N.	Questions
1	What are the key automation technologies implemented at Khalifa Port, and how have they improved operational efficiency?
2	What factors hinder achieving maximum operational efficiency through automation at Khalifa Port, and how does this impact its competitiveness?
3	How has automation contributed to reducing operational costs and increasing profitability at Khalifa Port without compromising service quality?
4	To what extent has automation accelerated cargo handling and reduced vessel turnaround time, enhancing operational efficiency?
5	How has automation impacted Khalifa Port's competitiveness compared to leading regional and global ports?
6	What role does automation play in improving the efficiency of supply chain operations and logistics services at Khalifa Port?
7	How has automation enhanced the quality of services at Khalifa Port, and how does this affect its ability to attract global customers?

6. Empirical analysis:

Individual interviews were carried out with a specific group of senior and middle managers at Khalifa Port, with consideration given to even distribution across different levels and administrative specialties pertaining to the study. The sample comprised middle managers and senior managers from top management, strategic planning, strategic project management, business development, commercial services, and customer services. This broad sample made it possible to address the multidimensional effects of automation from an operational, strategic, commercial, and service perspective.

The interviewees were chosen based on their hands-on experience, direct decision-making involvement, and supervision of operational or strategic roles at the Port. This functional diversity among interviewees adds depth to the findings and enhances the trustworthiness of the qualitative analysis, given the variety of viewpoints brought about by divergent organizational divisions and individual responsibilities. This diversity also increases the study's scope and adaptability to assess automation's effects on the operational competitiveness of the Port. The participants included the following:

i. **General Manager – Khalifa Port:**

The General Manager considers automation a big opportunity to enhance the port’s performance in terms of operational efficiency and financial sustainability. From this viewpoint, automation can enhance the efficiency of the use of the means of production, decrease operational failure zones, and provide uninterrupted services of the same quality. Overall, top management focuses on integrated operational and financial results that enhance the port's sustainable competitive advantage.

ii. **Vice President – Strategy Development:**

The Vice President of Strategy Development looks at automation from a competitive advantage perspective, defining it as a sustainable choice for the port over time. This perspective emphasizes building competitive advantage for the port by integrating automation solutions with the port’s envisioned future and subsequently improving the port’s structural capability to respond to global supply chain changes. The perspective importantly notes that the value of automation, in this instance, is only as part of an overarching digital transformation strategy.

iii. **Director – Strategic Projects:**

The Director of Strategic Projects primarily focuses on evaluating automation from a transformation perspective coupled with change management. This Executive Position is responsible for transforming automation opportunities into actionable initiatives, while also considering system integration complexities, maintaining uninterrupted operations throughout the integration, and attaining the target operational values. In this regard, operational cycle time and reduction of operational held the highest indicator of success.

iv. **Director – Business Development:**

The Director of Business Development associate's automation with market valuation and customer proposition. In this regard, automation is perceived as a positive facilitating factor for operational speed and accuracy; competitive service, and enhanced soft and hard linkages with line, international, and cross-border customers.

v. **Senior Manager – Customer Service:**

The Senior Manager of Customer Service considers automation from the customer experience and service quality perspective. In this role, automation is perceived as the enhancement of transparency, accuracy of information, speed of response, and reduction of operational complaints. Automation builds customer confidence and satisfaction and enhances the reputation of the port as a service.

6. Vice President – Commercial:

The Vice President of Commercial Affairs believes that improving profitability and strengthening the port's commercial competitiveness can be achieved through the automation of port processes. This perspective focuses on the positive aspects of automation in minimizing operational expenses, maximizing operational capacity, and enhancing profit margins that can subsequently lead the port to adopt more flexible pricing structures and enter long-term contracts. Within this context, the value of automation lies in the measurement of commercially sustainable performance.

Since operational efficiency is greatly improved by automation technologies, Khalifa Port's General Manager, refers to systems, terminals, and operational automation, including cranes, smart gating, and real-time container tracking. These technologies have improved productivity on the berth, reduced the need for manual operations, improved accurate planning for operational execution, optimally utilized resources, and reduced operational waste. However, while he appreciates the improvements, he identified the maximization of automation's benefits as a challenge. These challenges include the substantial amount of capital investment needed for the automation, the difficulty of creating and integrating systems digitally with external supply chain partners, the need for organizational change management along with the upskilling of the employees, and how this all leads to a reduction in a potential operational gain and the competitive advantage of a port that is advanced in its digital use. Khalifa Port is now operating from a digitally advanced and cost-efficient frame, and the reduction of operational costs because of the reduction in the need for manual labor, the increase in operational errors, and the utilization of equipment and operational assets, has positively impacted the financial profitability and improved the operational stability and the overall performance of the port, enabling the port to sustain its financial position in the long term.

The Port's use of automation tools has improved the scheduling of berths, increased the productivity of cranes, and reduced the turnaround time of vessels. This has solidified schedule reliability for shipping lines and has decreased the amount of time vessels wait at the Port. As a result, the Port has also gained more recognition on a regional and global level for the use of advanced technological automation systems. The use of automation has contributed positively to the Port's supply chain activities and to the enhanced coordination of cross-docking with the logistics processes. Furthermore, operational supply chain barriers have been eliminated, which has improved the flow of information among the relevant stakeholders, and has decreased the overall time spent on logistical activities. Increased visibility, accurate and speedy data processing, and quick responsiveness have improved the quality of service and elevated the level of trust among the customers, which has resulted in the Port attracting more shipping lines and international business customers.

The Vice President of Strategy Development stated that Khalifa Port has begun viewing automation as the first step in moving towards a data driven smart port model. Technologies that support advanced analytics have aided in operational planning and have prompted more proactive decision making. However, he stated that operational automation's full strategic impact is limited by several factors, the most important of which is the strategic misalignment of certain automation solutions with the port's most valued future state, as well as challenges with integrating certain supply chain partners. Such gaps may reduce the strategic value of automation and undermine the port's sustainable competitive advantage. From an operational and financial perspective, automation has benefitted the port by digitally reengineering processes and exploiting economies of scale, all while improving service quality through enhanced operational control and compliance with service quality performance standards. Automation also improved inter-stage operational coordination, which in turn improved the integration of mid and end stage operational planning with real time operational actions, thus improving maritime operational flow and reducing the time vessels wait to be serviced. On a competitive level, automation has improved Khalifa Port's competitive advantage by improving reliability and performance predictability which has improved the Port's competitive advantage over rival Ports.

The port's enhanced integration into global supply chains has further improved resilience and efficiency of logistics services by reducing the response time to disruptions. Finally, due to port automation, service quality improvements have increased the port's competitiveness to global firms that value a sophisticated and digitally seamless operational ecosystem.

Operational streamlining and reduced manual intervention, along with enhanced operational productivity, have been achieved through automation of Khalifa Port, as stated by the Director of Strategic Projects. Automation at Khalifa Port, however, has been complicated owing to challenges pertaining to the management of change, the merging of outdated and new technological systems, the breadth and depth of training needed, and the impact of such challenges on the operational returns. In addition to such challenges, automation has also aided in the financial aspect of Khalifa Port by reducing costs through operational, maintenance, and billing efficiencies achieved in the financial management of services rendered. In addition to these benefits, automation has also reduced the duration of operational cycles and the efficiency of process flow, thereby reducing the turnaround time for vessels and enhancing the speed of cargo operations. Automation at Khalifa Port has also increased the operational and competitive capability of the Port by improving the integration of operational systems of the supply chain. In addition, the projects have improved reliability and reduced the margin of operational errors, which has positively impacted on the confidence of customers in the services of the Port.

The Director of Business Development stated that from a business development perspective, automation at Khalifa Port has improved the value proposition to customers by enhancing the speed and accuracy of operational processes. However, he pointed out that one of the primary constraints is the varying degrees of digital readiness of supply chain partners, which may limit fully leveraging automation at the more encompassing supply chain level. With the automation, the Port can offer more competitive prices because of reductions in operational costs while service levels remain unchanged and, in some cases, improved. The Port is more attractive to customers and shipping lines because of the improved service, which includes quicker cargo releases and less time waiting for vessels to be turned. The port is also regionally more competitive than it was due to the ability to provide consistent and timely service. It has also met the Integrated Logistics Service needs of customers internationally, which has improved service quality and provided additional competitive advantage. Ultimately, improved service quality due to automation has enhanced the attraction of the Port to new customers and to foster existing customers for long-term business relationships.

The Senior Manager of Customer Service said that the automation within Khalifa Port is helping customers since customers can track shipments in real time and receive digital updates, meaning they do not have to communicate with customers manually. However, a major challenge is the consistency and accuracy of the data, as any gaps in the data can negatively impact on the customer's trust. Despite this, automation is helping employee costs and service quality, as less complaints and quicker resolutions to issues have reduced customer service costs. It has also resulted in customers being served in a timelier manner and improved adherence to service level agreements. From the customer's view, the improved service has helped the perception of the port as an automation service. The enhanced service level has also helped supply chain coordination and logistics planning, leading customers to view the port more favorably. The port has also improved its position as a logistics center.

The Vice President of Commercial Affairs remarked that Khalifa Port's automation has encouraged commercial progress by providing greater operational efficiency and increasing the port's capacity for cargo processing. Significant challenge remains, however, in justifying long-term ROI for automation initiatives, given the pace of technological change. The operational cost savings from automation have positively impacted on the profit margin, all while maintaining high levels of service. Enhancing the port’s allure commercially was speedier cargo processing and less time vessels had to wait. Additionally, Khalifa Port’s competitive landscape in the global and regional port was bolstered by improved customer automation. Commercially, the Port’s automated solution and position with the global supply changed was further enhanced. Finally, the quality of digital services has attracted international clients and solidified commercial relations for the long haul.

7. Conclusion:

The findings from the interviews suggest that the role of automation in improving Khalifa Port's operational efficiency is universally accepted by all participants, although the agreement was expressed through different lines of analysis shaped by the participants' positions and roles in the organization. From a senior management standpoint, automation was viewed as a structural component of the institution's overall performance, relating it to better asset productivity, enhanced financial viability, and operational risk minimization, indicative of a management layer who views automation from a predominate institutional competitiveness prism. The strategic echelon, however, articulated an even more expansive time horizon, viewing automation as a strategic investment to engender a sustainable competitive advantage, in contrast to the integrated digital transformation, framed within Port authority organizational agility and the adaptive responsiveness to the global supply chain, consistent with prevailing literature on strategic port management. From the other end of the spectrum, in the executive tier, particularly represented by strategic project management, participants alluded to the conceptual and practical operational impediments of systems integration, and the operational management of continuity, which is indicative of a possible gap in design versus operational execution, and more critically a gap in the alignment of the intended strategic vision and the operational and practical capacity to realize the automation.

Automation, from a Business Development perspective within a market-oriented framework, was viewed in the context of value generation, which, by virtue of its capability to facilitate swift and dependable service provision, enhances the port's commercial viability and fosters business growth and enduring commercial relationships. As with Customer Perspective, the success of automation should not only be measured by the operational performance, but by the impact on the service dimension, such as quality, transparency, accuracy of information, speed of response, and other issues, which are critical to customer trust and competitive position from the end-user's perspective. Certainly, from the commercial perspective, automation, in the case of ports, was directly related to profitability and return on investment, as it lowered the costs of operations, and increased the capacity of the ports, which combined with service quality, offered the flexibility to the pricing and more competitive operational structures. All the above viewpoints indicate that, when considering the phenomenon of automation in the ports, it should be treated as a complex, multidimensional phenomenon that transcends the boundaries of purely technological solutions to address the strategic, operational, commercial, and service aspects of the phenomenon simultaneously. The diversity of viewpoints, in the author's opinion, is a manifestation of functional complementarity, as opposed to contradiction, in that each perspective adds to a more complete picture of the role that automation plays in enhancing operational efficiency and, more importantly, the competitive position of the ports.

The following recommendations have been constructed in line with the interviews conducted with the leaders in each function at Khalifa Port. These recommendations seek to optimize the impact of automation on operational efficiency and competitiveness.

- Strategic Recommendations: In terms of digital strategy, there will be a need to align all automation projects with a comprehensive integrated long-term digital strategy. This is to make sure that automation projects do not become siloed and instead, each project aligns with a pathway providing a roadmap to the development of a data-driven smart port. Another suggestion offered is the establishment of a digital governance framework to align automation stewardship with the strategic objectives of competitiveness, sustainability, and operational resilience.

- Operational Recommendations: System integration and digital platform unification should be enhanced to streamline and minimize redundancy in the digital architecture. Increased seamless data flow will be facilitated. In order to reduce unplanned outages and improve the utilization of copes, increased investment in smart maintenance and predictive analytics will reduce operational cycles and increase productivity on the berths and with the equipment.

- Managerial and Implementation Recommendations: Across interviews, a recurring theme is the challenge of managing change when it comes to automation. Thus, institutional approaches to workforce training and building a digital culture at the port are necessary. Also, applying adaptive project management practices will likely promote the seamless merging of legacy and modern systems while maintaining operational flow.

- Commercial and Market-Oriented Recommendations: Automation should be viewed as a competitive advantage to positively market the port in terms of reliability and turnaround times. It is also suggested that the port operator implement approaches that optimize pricing as operational efficiency improves. Additionally, enhanced digital connectivity with shipping lines and logistics partners is likely to support the provision of composite, intelligent, and prompt services.

- Supply Chain–Related Recommendations: Enhanced digital interconnection with external supply chain partners through shared data systems and standardized data exchange protocols will help eliminate blind spots in cargo movement and visibility. It also improves the port's adaptive capacity and responsiveness to international shocks.

- Customer Service Recommendations: We recommend the continued advancement of real-time tracking systems, digital gateways, and customer dashboards to improve transparency and responsiveness. Also, customer satisfaction metrics should reflect the outcomes of automation performance indicators to align technological advancements with improvements in user experience.

- Financial Recommendations: Stronger frameworks should be in place to assess the ROI of automation, including a regular cost versus operational and commercial benefit assessment. Furthermore, to sustain a competitive advantage, it is necessary to reinvest the savings generated into more sophisticated automation systems.

In the future, researchers must develop both the quantitative and qualitative dimensions of the understanding of automation's impact on port performance—especially operational efficiency, financial returns, and supply chain resilience. Important dimensions include developing frameworks for assessing the financial performance of automation, understanding how digital technologies impact responsiveness to global disruptions, and understanding the automation impacts on employability skills and the adaptive capacity of organizations. Additional research is also needed on smart ports and their integration with extended logistics networks, the use of artificial intelligence and predictive analytics for operational decision-making, and automated ports across the globe to develop comparative analyses and best practice frameworks. Also, research on customer experience, digital governance, environmental sustainability, governance, and the cyber resilience of ports will contribute to informing an understanding of automation as the main driver of strategic, operational, and sustainable transformation in modern ports like Khalifa Port.

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Port State Control Memorandums of Understanding: The Opportunity of an Integrated Regional Regime

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المستخلص

تتناول هذه الورقة درجة الموائمة والتناغم بين مذكرة تفاهم باريس لرقابة دولة الميناء (Paris MoU) ومذكرة تفاهم البحر المتوسط (Med MoU). ورغم أن النظامين يستندان إلى نفس الصكوك الصادرة عن المنظمة البحرية الدولية (IMO) ومنظمة العمل الدولية (ILO)، فإن التطبيق يختلف بين الأقاليم، بما يؤثر في قابلية التنبؤ والموثوقية في إنفاذ المتطلبات.

تم اعتماد تصميم بحثي مختلط يشمل: (١) تحليلا وثائقيا وكمياً لإحصاءات مذكرات التفاهم الرسمية للفترة ٢٠٢١-٢٠٢٣ (التفتيشات، الحجوزات، معدلات الحجز، العيوب، وأدوات الإنفاذ)، و(٢) تحليلا موضوعيا لإجابات استبيان مفتوحة لخبراء ومهنيين مرتبطين بأنشطة رقابة دولة الميناء (N=122). تُظهر النتائج وجود فجوات مستمرة في حجم التفتيش ومخرجات الإنفاذ؛ إذ سجلت مذكرة تفاهم باريس ١٥,٤٠١–١٧,٢٨٩ عملية تفتيش سنويا بمعدلات حجز تراوحت بين ٣.٤٩–٤.١٨%، بينما سجلت مذكرة تفاهم البحر المتوسط ٤,٩٥٤–٦,١٣٢ عملية تفتيش بمعدلات حجز بين ٢.١٢–٢.٦٠%. كما تختلف أنماط العيوب؛ حيث تُظهر مذكرة تفاهم باريس تركيزا أعلى في مجالات السلامة من الحريق وفق اتفاقية SOLAS والهيكل/المحركات، في حين تُظهر مذكرة تفاهم البحر المتوسط تكرارا أكبر لمشكلات الوثائق والملاحة، مع تفاقم مسألة عدم مواءمة ترميز العيوب. وتبرز الأدلة النوعية خمس أولويات متكررة: تدريب وكفاءة مفتشي رقابة دولة الميناء (PSCOs)، التناغم في الإجراءات، التحول الرقمي وعدم تكافؤ نظم تقنية المعلومات (THETIS مقابل THETIS-Med)، عدالة التفتيش، والتشظي القانوني والمؤسسي.

تقترح الورقة مسارا عمليا مرحليا للتناغم والتكامل يرتكز على توحيد ترميز العيوب، ومواءمة نطاق الاتفاقيات، واعتماد مؤشرات أداء مشتركة، وبناء القدرات بدعم منصات رقمية قابلة للتشغيل البيني. وكخطوة إضافية نحو التقارب العالمي، تعرض الدراسة إطارا مرحليا لمواءمة مذكرات التفاهم فيما بينها (MoU-to-MoU) يقوم على معايير بيانات مشتركة، والاعتراف المتبادل بنتائج التفتيش، تنظيم تقييمات دورية مشتركة (بما يشمل مراجعات متبادلة وحملات تفتيش منسّقة). وضمن هذه الخارطة، تُعد الأولويات الأساسية إنشاء قاعدة بيانات إقليمية مركزية للمنع/الحظر، وتوحيد التدريب الفني لمفتشي رقابة دولة الميناء (PSCOs)، وتعزيز قابلية التشغيل البيني الرقمية بين الأنظمة، بما يحد من فجوات الإنفاذ ويقضي على "الملاذات السالمة" للسفن دون المستوى، دون اشتراط دمج مؤسسي فوري.

Abstract
This study examines the degree of harmonization between the Paris Memorandum of Understanding on Port State Control (Paris MoU) and the Mediterranean Memorandum of Understanding (Med MoU) as they relate to the International Maritime Organization and the International Labor Organization (IMO/ILO). Even though both agreements were developed from the same international instruments, they are applied differently in each jurisdiction; therefore, the way each jurisdiction applies them results in an unequal level of predictability and credibility when enforced.

The research study employed a mixed methods methodology to gather data and respond to the research questions from an evidence based data analysis methodology. The authors analyzed the data using two forms of data analysis: a quantitative analysis of 2021-2022 last MOU official statistics (documentary) and a thematic analysis of open ended questionnaire responses from 122 PSC professional participants; this created the data set used to answer the study objective. Of interest is the difference in the number of inspections performed and the number of enforcement actions taken from those inspections. For instance, the Paris MoU inspection numbers ranged from a high of 17,289 inspections to a low of 15,401 inspections conducted between 2021 to 2023, with the average detention rates per inspection between 3.49% and 4.18%. In comparison; the Mediterranean MOU's numbers of inspections were a low of 4,954 inspections to a high of 6,132 inspections conducted over the same three years' timeframe, with average detention rates per inspection between 2.12% - 2.60%. In addition to the discrepancies in numbers of inspections performed and types of enforcement actions taken, the findings also indicate differences in deficiency profiles and enforcement focus between MoUs related to their potential definitions of deficiencies caused by SOLAS fire protection, structural integrity, and others (i.e. documentation, navigation, and safety). The interview data also indicated that there are five recurring issues with the continuing fragmentation of the PSC system. These include: (1) A lack of competence or training for the PSCO; (2) a need for procedural harmonization, (3) the status of digital technologies (THETIS versus THETIS-Med), (4) fairness in the inspection process, and (5) legal/institution fragmentation.

A phased plan for integrating and unifying varying regulation types consists of a standard series of deficiency coding; a clearly defined scope of conventions to be adhered to; shared performance indicators and the provision of capacity building programs utilizing interoperability of digital technology networks will be created. Additionally, the Phased Approach outlines a series of steps that can be taken in order to assist with global convergence which also includes the creation of common data standards for aligning MoUs to each other and mutual recognition of inspection results and the periodic calibrated inspections as well as concentrated campaigns. Some of the major areas of concern that have been identified that will be integral in achieving these objectives as part of the roadmap are as follows: (1) creating a centralized regional database of banned ships; (2) standardizing technical training for Port State Control officers; (3) identifying innovative digital methods to reduce the disparity between methods of enforcement for both types of regimes;

and (4) eliminating the ability for substandard vessels to utilize "safe havens" to conduct their operations without requiring an immediate merging of the MoUs.

Keywords: Port State Control (PSC); Paris MoU; Mediterranean MoU (Med MoU); Harmonization; Deficiency Coding; Digital Interoperability (THETIS/THETIS-Med)

1. INTRODUCTION

Ensuring safety & protecting our oceans is not one or the other but both are global priorities reliant on a multitude of international regulations. The “flag states” would primarily be accountable for ensuring their vessels are compliant with global standards, however, there are now too many international open registries without sufficient administration and oversight leading to the requirement for a second line of defense for compliance with international conventions through PSC (port state control), giving port states the opportunity to perform inspections of foreign-flagged vessels at their respective ports to confirm compliance with the International Convention for the Safety of Life at Sea (SOLAS) and the International Convention for the Prevention of Pollution from Ships (MARPOL), as well as other vital instruments.

The world is now divided by regional MoUs as a result of the establishment of the first regional agreement, the 1982 Paris Memorandum of Understanding (MoU). There is much benefit in this division because of the ability to share information/resources and cooperate in targeting, however; regionalization of PSC has created an important challenge; namely, fragmentation. If the inspection regimes in one region are rigorous and the neighboring area's inspection regime is lenient, non-compliant vessels can participate in so called "port shopping", using their international trade routes as their method of avoiding detection.

This study analyzed how closely the Paris MoU and the Mediterranean (Med) MoU are aligned. Due to the maturity of its risk based targeting and the sophistication of its transparency instruments and digital technology/infrastructure, the Paris MoU is frequently used as a point of reference for comparison. The Med MoU has had a long standing history of containing a strategically significant maritime transit corridor; however, historically, it has varied in inspection capacity, the amount of inspection conducted, and has lagged in developing digital technology. Recently, the launch of THETIS-Med, which was inspired by the Paris MoU THETIS model, provides an opportunity to reduce the operational differences between the two organizations and more effectively support regional cooperation.

The objective of this paper is to provide an evidence-based comparison of the two regimes (2021-2023) and to integrate practitioner perceptions, thereby identifying concrete, implementable measures that can support deeper harmonization.

Although previous studies have addressed PSC harmonization in general terms, fewer studies combine recent official comparative data with practitioner evidence to assess harmonization specifically between the Paris and Mediterranean MoUs.

2. METHODOLOGY

A mixed method strategy was used in this study where both quantitative statistical data and qualitative data collected, through surveys with participants, were utilized to provide the foundation for triangulated results produced from the research.

2.1 Quantitative Data Collection

The official Annual Reports from both the Paris and Mediterranean Memoranda of Understanding (MoU) were compiled in accordance with the most recent years reported for these documents (i.e., 2021, 2022, and 2023). The extracted data that will be utilized in this analysis include the following variables related to the number of inspections performed on foreign flag vessels:

- The volume of inspections performed was measured in terms of the number of initial inspections conducted.
- The detention rate will be calculated as the percent of inspections resulting in detention.
- The categorization of deficiencies (e.g., Fire Safety vs. Documentation).
- Statistics representing the frequency of refusal of access orders issued will contribute to determining frequency and severity of deficiencies overall.
- Data was also cross-referenced with the IMO Global Integrated Shipping Information System (GISIS) and Equasis to verify trends.

2.2 Qualitative Survey Design

To analyze the "why" behind the patterns in the statistics, an online structured questionnaire was sent to maritime professionals. The questionnaire targeted maritime professionals engaged in PSC related practice within the Euro-Mediterranean context, including PSCOs, ship owners and managers, seafarers, and other maritime professionals.

- Sample Size: The number of valid responses was 122.
- Demographics: The respondent pool consisted of 27% PSCOs, 26% Ship Managers, 20% Seafarers, and 27% Other Maritime Professionals.
- Instrument: The survey was composed of 20 items measured by Likert-type (1-5) scales measuring various topics including perception of effectiveness, perceptions of fairness, and perceptions of harmonization, in addition to providing open ended questions.

2.3 Data Analysis

Descriptive statistics were used to identify comparative trends across the two regimes, while open-ended responses were coded thematically to identify recurring patterns related to harmonization and enforcement.

The qualitative component was intended to interpret the operational reasons behind observed statistical differences rather than to generate statistically generalizable findings.

3. RESULTS

3.1 Quantitative comparison of inspection activity and enforcement outcomes

Table (1) Paris MoU inspection activity (2021-2023)

Year	Inspections	Detentions	Detention rate (%)	Deficiencies	Detainable deficiencies	Banning
2021	15401	537	3.49	36272	3352	11
2022	17289	723	4.18	47167	4873	10
2023	16769	639	3.81	47510	4809	11

Table (2) Med MoU inspection activity (2021-2023)

Year	Inspections	Detentions	Detention rate (%)	Deficiencies
2021	4954	104	2.12	10087
2022	6132	132	2.2	16065
2023	5976	157	2.6	14449

Paris MoU inspection activity rebounded after the COVID-19 slowdown, increasing from 15,401 inspections in 2021 to 17,289 in 2022, then stabilizing at 16,769 in 2023. Detentions peaked at 723 (4.18%) in 2022 before declining to 639 (3.81%) in 2023. In parallel, the number of deficiencies remained high, exceeding 47,000 in both 2022 and 2023, with detainable deficiencies remaining above 4,800 in 2023.

Med MoU inspection volume was substantially lower, ranging from 4,954 to 6,132 inspections. Detention rates increased gradually from 2.12% (2021) to 2.60% (2023), with 157 detentions recorded in 2023. The scale difference is structurally linked to membership size, port network coverage, and PSCO availability.

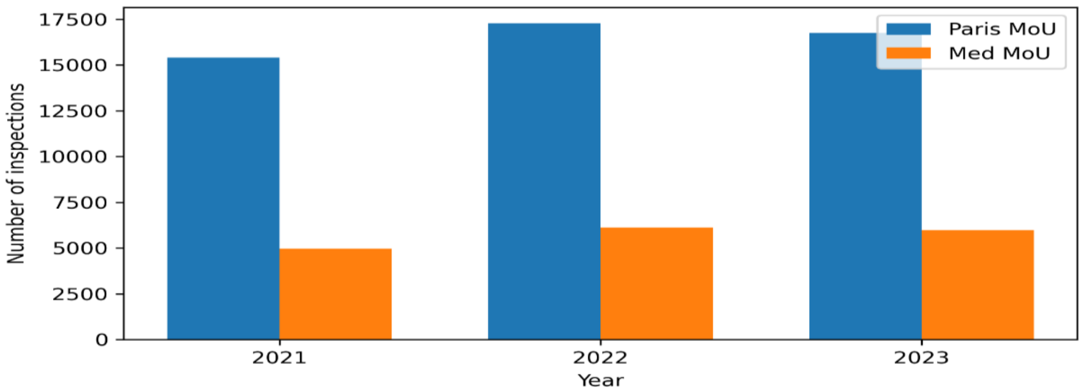

Figure (1) Inspections (Paris vs Med MoU, 2021-2023)

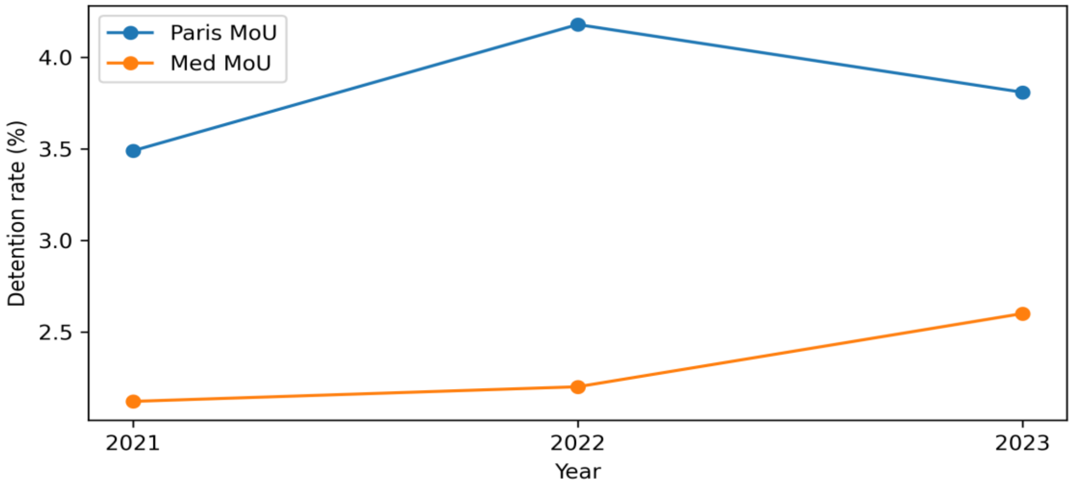

Figure (2) Detention rate (Paris vs Med MoU, 2021-2023)

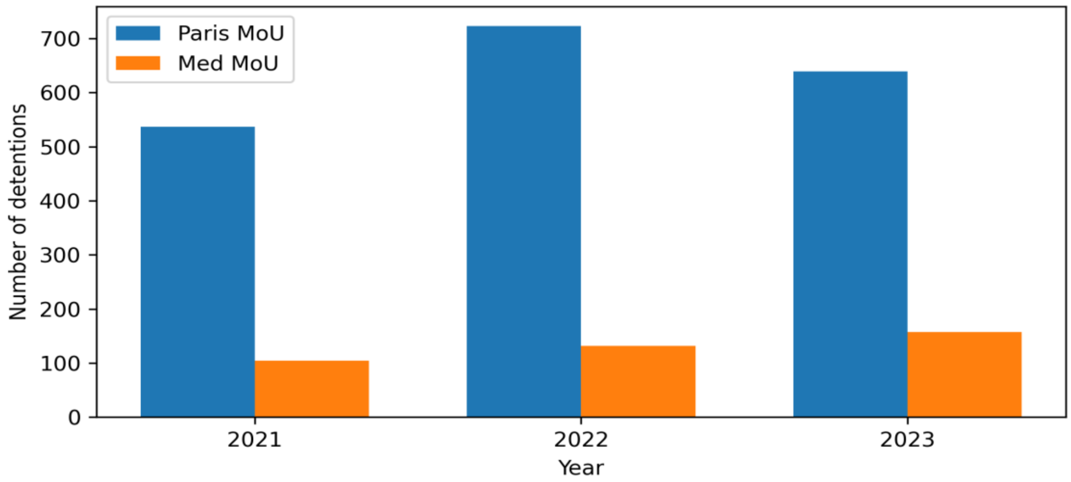

Figure (3) Detentions (Paris vs Med MoU, 2021-2023)

3.2 Deficiency patterns and comparability constraints

The two regimes display different deficiency profiles and enforcement emphases, which limits direct comparability. Deficiency counts were substantial in both regimes, but category structures and coding practices complicate direct comparison. Numbers from the Paris MoU in 2023 showed that they found 48,000 deficiencies with 17% related to fire safety, 12% to hull/machinery, and 10% for living and working conditions (MLC title 4). In the Med MoU, 14,449 deficiencies were reported, and showed a stronger concentration in documentation and navigation related issues.

The absence of fully harmonized deficiency coding results in analytical restrictions for comparisons between the two regimes due to limitations on the ability to map categories directly and analyze trends across categories. This will cause an inequivalent level of enforcement focus between the two regimes, increasing the difficulty of establishing a common baseline of risk indicators.

3.3 Qualitative themes from practitioner responses

Thematic analysis was performed on the answers from an open ended survey (N=122) which identified multiple trends and themes within participant responses in regards to human and institutional variables impacting harmonization. Five themes overall were revealed from this analysis, which were: (i) quality and training of PSCOs; (ii) perceived harmonization of MoUs; (iii) digitalization and IT asymmetry (THETIS vs THETIS-Med); (iv) fairness and consistency during inspections; and (v) legal/institutional fragmentation.

Table (3) Summary of qualitative themes derived from questionnaire responses (N=122)

Theme	Responses (n)	Indicative prevalence	Representative view
Training and competence of PSCOs	~75	High	There is a huge lack of qualified PSCOs.
Harmonization between MoUs	~68	High	Procedures are similar in theory but not in enforcement.
Digitalisation and THETIS / THETIS-Med	~60	Medium-High	The system is useful but more training is needed.
Inspection effectiveness and fairness	~55	Medium	Criteria vary between ports.
Legal and institutional fragmentation	~40	Medium-Low	Each State applies rules differently.

4. Discussion

The comparative evidence indicates partial convergence at the level of legal foundation, but continuing divergence in operational intensity, transparency, and enforcement practice. While both share a common base of conventions upon which to establish inspection and detention models, they are very different with respect to enforcement intensity, enforcement transparency tools, and level of maturity in their operational capabilities. By the number of inspections occurred at each MoU, Paris MoU was inspecting approximately 3 times more than was the Med MoU from 2021 - 2023, and likewise, the Paris MoU detention rates were consistently higher than those of the Med MoU. By the qualitative perspective of the respective stakeholder communities; stakeholders agree that the processes used by each MoU to enforce convention occurrences are similar in concept, but differences exist in enforcement outcomes resulting from differing levels of PSCO training, differing degrees of port level discretion, and differing levels of digitalization maturity.

The main reason that Digitalization serves as a major convergence lever is through the use of traceable histories, risk based targeting, and transparency outputs found within the Paris MoU's THETIS. The launch of THETIS-Med in 2022 improves the ability to close the information technology gap between inspectors; however, it was expressed by all of the survey respondents that digital tools do not serve to replicate standardized human level competencies, consistent deficiency coding, or the establishment of mutually aligned follow up protocols.

In addition, the enforcement environment also has differences in terms of a more openly stated prohibition of access (in other words banning) enforcement in the case of the Paris MOU facilitating higher levels of deterrence and reducing chances of repeat non compliance. The lack of transparency and performance benchmarking for the Med MOU means that there is less external pressure for accountability and may provide less incentive for both underperforming flags and recognized organizations to take action to improve their standards.

4.1 The "Two-Tier" Safety Regime

Taken together, the quantitative and qualitative findings suggest the emergence of a two-tier enforcement environment within the Euro-Mediterranean space.

- **Tier 1 (Northern Tier):** High Levels of Transparency, Rigorous Technical Inspections, and a Credible Deterrent (Banning).
- **Tier 2 (Southern Tier):** Characterized by lower detention rates, administrative focus, and limited transparency.

The creation of this bifurcation has produced a market distortion which is referred to as "Regulatory Arbitrage." Substandard vessel operators can use these differences by sending their ships to ports with less statistical chance of being detained. This situation harms the overall safety of the entire maritime industry.

4.2 Institutional Isomorphism vs. Reality

Institutional Theory suggests that organizations try to resemble their successful peers. The Med MoU has attempted this by adopting the form of the Paris MoU (e.g., adopting THETIS-Med software). However, the results show that adopting the tool without the culture (transparency, strictness) leads to "decoupling." The software exists, but the rigorous data entry and follow up required to make it effective are lagging.

4.3 The Role of the Human Element

The study identifies the "Competence Gap" as the primary transmission mechanism for harmonization. Legal texts (conventions) are identical, but their interpretation relies on the individual inspector. Without standardized, rigorous technical training, a PSCO in the south may interpret a "corroded fire main" differently than a PSCO in the north. Harmonization depends not only on common legal texts but also on calibrated inspector judgment, standardized training, and consistent follow up practices.

5. Conclusion and Recommendations

5.1 Conclusions from quantitative evidence (2021 - 2023)

From comparing the data, we can see that the Med MoU is being developed and more consistently established as a tool in every member to this MoU. Meanwhile, the Paris MoU has achieved a level of maturity and has developed a well structured PSC regime.

i. **There are two different kinds of capacity which pertain to the maturity of a system as well as its respective capacity.** When the inspections carried out by PSC in Paris MoU and Mediterranean MoU were compared with each other, we found a significant differences in numbers where 15,401 vs 4,954 in 2021, 17,289 vs 6,132 in 2022, and 16,769 vs 5,996 in 2023, as shown in Tables 1 and 2. Total figures of PSC inspections in each region provide obvious evidence into variations in maturity (quality & discipline) within institutions that have contributed to the establishment & implementation of their country's particular regional agreement.

ii. **The intensity of operational enforcement varies substantially.** The Paris MoU has relatively high rates of detention as indicated in the data contained within Tables 4-1 & 4-2 and Figure 4-2 (3.49%, 4.18% and 3.81% respectively compared to 2.12%, 2.20% and 2.60%;) although higher rates of detention may not produce better results than lower rates. When comparing qualitative aspects of varying methods of enforcement that escalate, The Paris MoU demonstrates a more structured escalation framework, which likely strengthens deterrence and follow up consistency.

iii. **The deficiencies in these systems correspond to different styles of review, or types of depth and focus, for material.** A review of deficiency categories indicates the two systems are deficient in different categories when being evaluated and inspected. For example, the inspection system would have deficiencies identified that have more to do with document than deficiencies related to the technical or safety aspects. Whereas, the other system would have deficiencies identified more related to the safety of a ship than to documents.

iv. **Transparency and escalation tools are one of the primary differences between these two structures.** One of the major distinctions between the Paris and Med MoUs is associated with transparency and escalation. The PSCO policies in the Paris MoU define a number of actions regarding escalation, such as when to refuse access and to apply formal bans. The established notification procedures for the public provide a greater level of deterrence, which allows for consistent enforcement of the maritime regulations. On the other hand, the Med MoU operates under a general principle of transparency but currently does not have any established procedures for escalation or transparency, and consequently will likely continue to be perceived as less reliable, from an enforcement standpoint, than the Paris MoU.

The findings suggest uneven enforcement intensity across the Euro-Mediterranean space, creating conditions that may enable regulatory arbitrage.

5.2 Conclusions from qualitative evidence (survey, N = 122)

The results of the survey show that stakeholders generally believe there is a common legal base for shipping operations (SOLAS, MARPOL, STCW, MLC, etc) within their respective jurisdictions. However, there are also serious reservations about the consistency, effectiveness and fairness of the outcomes of the various jurisdictions.

The practical explanation for the reason behind the numbers, as provided by the survey results:

- Some of the most common themes in the responses rotate around competencies and training, such as professionalizing and enhancing multi-discipline inspector groups/teams. Approximately 75 responses for additional training were submitted along with requests for professionalization of multi inspectors vs reliance on single inspectors and making improvements to the inspection processes.
- There is a significant discrepancy between how ports are perceived as having similar procedures and how these procedures are actually implemented. Examples of this discrepancy include the degree of coordination among port or administrative procedures, and the similarities in procedures recorded at ports that actually have similar administrative procedures. (~ 68)
- A considerable number of respondents (~60) have provided responses with a relatively strong correlation between the digitalization asymmetry (both established/enabling vs. transitional/developing) as represented on the THETIS Platform and the maturity of the THETIS-Med system (i.e., how far THETIS-Med has been developed).
- Several stakeholders (~55 responses) who evaluated inspection effectiveness and fairness found no clarity as the admins appeared to only focus on the following two indicators of effectiveness: (1). meeting target coverage (i.e., coverage of inspections) and; (2). whether the data produced through inspections (e.g. monthly reports) showed any evidence of effectiveness. Conversely, the resources and industries within the shipboard industry were also concerned with safety outcomes, i.e. if accidents occur; providing predictability, and consistent inspections (i.e. they should happen the same way every time).
- Although some of the responses referred to integrity concerns based on perception (i.e., bribery or non-technical influence), they were only regarded as being based on perception rather than being attested to as factual. However, it is important to note that damaged credibility and compliance culture could have occurred due solely to perception.

5.3 Recommendation set

The following recommendations have been written clearly to include a responsible person, implementation timeframe, and intended outcome.

Table 4 – Prioritized Recommendations Matrix

Priority	Recommendation	Owner(s)	Timeframe	Expected effect
High	Regional interpretation & detention guidance compendium + annual calibration workshops	MoU Secretariats + member States	0-12 months	Reduces variability; increases predictability and fairness
High	Regional competence framework with documented refreshers and specialization tracks	MoUs + maritime administrations + MET partners	0-12 months	Improves inspection depth and technical consistency
High	THETIS-Med minimum data standards + user certification + periodic data quality audits	Med MoU Secretariat + members	0-12 months	Improves targeting reliability; reduces loopholes
Medium	Structured enforcement escalation alignment (including refusal of access mechanisms and follow-up)	MoUs + member States	1-3 years	Strengthens deterrence; limits repeat offenders
Medium	Cross-regime interoperability layer (standard deficiency coding + cross-alerts)	Paris/Med + IMO facilitation	1-3 years	Improves cross-region continuity and risk tracking
Medium	Public reporting template harmonization (selected indicators first)	MoUs	1-3 years	Builds credibility and accountability
Long	Global interoperability principles under IMO (without removing MoU autonomy)	IMO + MoUs	3-5 years	Scales integration toward global consistency

5.3 Recommendations by stakeholder group

- The MoU secretariats are not paying enough attention to how regulations are implemented and interpreted on the ground. Significant differences across regimes continue to exist; regular calibration of the different regulations would assist with these discrepancies. Also, greater clarity regarding digital governance and transparency, would increase the predictability of implementing them.

- The competence of PSCOs should not be viewed as an item that can be validated once and then discarded. PSCOs need to receive refresher training frequently and, therefore, it is important to maintain an effective record of PSCO competencies
- In some instances, PSCOs may need to have a greater level of technical expertise when inspecting complicated vessels. In addition, working with others versus being viewed on their own may assist in lessening the level of personal judgment differences.
- Shipowners / Operators also can assist with enhancing this process by performing internal self assessments regarding the most commonly identified deficiencies; thus, improving predictability where possible and employing a more open approach to correcting those deficiencies.
- The IMO may help with these initiatives by improving the availability of information about how to work together cooperatively, the sharing of data, and how to enhance the capacity of the parties working together. In addition, the structured interactions that result from cooperative agreements, as well as the harmonization of those cooperative agreements, will help to reduce the various current jurisdictional differences.

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