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Contents

Editorial

English Papers

Examining Employment and Retention Challenges of Non-Native English-Speaking Seafarers in the International Maritime Industry: A Quantitative Analysis

Soha Heikal, Alaa Abdelbarry, Mohamed Khatab, Ahmed Swidan, Mahmoud Mansi



Deep Reinforcement Learning for Optimizing Electronically Controlled Propulsion: A DDPG-Based Approach

Mohab M. Eweda, Karim A. ElNaggar



Aden Container Terminal's Future: Opportunities, Threats, and the Role of Private Sector Participation

Ashraf Qardash



Impact of Human Error on Maritime Industry: Case of Jamaica

Mazen Hussein, Said Abdelkader



Evaluating the Impact of AI Tools on the Performance of Maritime Trainees in METI

Ahmed Mohamed Aly Salem, Mohamed H. M. Hassan



POTENTIAL IMPACT OF EARTH'S REVERSAL POLARITY ON SAFETY OF NAVIGATION

Ahmed Yousry Elhabashy, Mahmoud Elbawab



Assessment of onshore power supply for ship's emissions reduction in Alexandria Port utilizing national grad/renewable energy.

Eng. Mahmoud Tahah Hassan, Dr. Nour Ahmed marey, Prof. Adel Abdallah Tawfik



Maritime Port Evolution: Balancing Operational Excellence with Zero-Emission Requirements in the Context of IMO 2050 Objectives

Mohamed Elhussieny



Assessing the Accuracy of Histogram Threshold and Band Ratio as a Shoreline Extraction Techniques from Low-resolution Sentinel-2 Satellite Imagery

Mohamed Elmeligy, Ahmed Elrabbany, Saad Mesbah, Mohmoud Hassan, Mohamed Mohasseb



Application of Human Factors Analysis and Classification System (HFACS-MA) vs Root Cause Analysis (RCA) in Investigation of Maritime Incident within Marine Ports

Lafi Mubarak Al-Azemi, Eslam Adel, Sameh Farahat



A Comprehensive Investigation into Full-Scale Characteristics Contributing to Seafarers' Psychological Security: Egyptian Seafarers as a Case Study

Nader S. Fahim, Amman A. Aly, Marwa M. Elkhateeb



Bridging the Gap: Modernizing Environmental Management Systems in Egyptian Seaports to Align with Global Maritime Transport Trends

Mohamed Elhussieny, Agne Jucyte Cicine



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Cybersecurity Threats in Maritime Autonomous Surface Ships Navigating Canals and Narrow Channels: A Risk Assessment Using STPA-Safety/Security and Fuzzy-AHP

Eslam Ramadan Badry Gad, Teona Khabeishvili



The Integration of ArcGIS Drone2Map with ArcGIS Pro Software to Solve the Miss Alignment in Processed Drone Data to Extract Shoreline

Mohamed Elmeligy, Ahmed Elrabbany, Saad Mesbah, Mohamed
Mohasseb



The Negative Impact of Complacency on the Seafarer's Attitude and Behaviors

Hesham Mohamed Eldabe



Assessing the Impact of Automating the Operational Processes at Khalifa Port Using Swot Analysis

Hazzaa Mohamed Aljneibi, Hesham Helal, Mohamed Elkersh



Arabic Papers

The Impact of Applying Sustainable Development Dimensions through Modern Technology on the Operational Performance of Seaports: An Applied Study on Misrata Seaport

Abo Bakr Abdulkah Salem Kajom



Competitiveness Analysis of Container Ports: Comparative Study between Aden Port and Regional Ports

Shakib Mohamed Abd EL-Wahed, Osama Fawzy Al-Bayoumy



The Mediating Role of Innovative Work Behavior in the Relationship Between Talent Management and Job Performance: A Case Study of the Ports and Maritime Affairs Authority in the Republic of Yemen

Zulfi Ahmed Abdwin, Mohamed Wahba Mohamed, Eman Ismail
Naseef



Analysis of the role of modern technologies in improving container management at the port of Aqaba

Zaid Wael Al_Hroop



The role of smart ports in improving the operational efficiency of seaports

Abdulmalik Omar Farhat, Sameh Farhat, Mukhtar Al-Habashi



Development of Infrastructure and Organizational Improvements to Enhance the Efficiency of the Sokhna Dry Port

Mohamed Ibrahim Mahmoud Abd El-Rahim, Osama Fawzy AL-
Bayoumi, Ayman Gamal Ali



Available Online

The role of logistics management as a catalyst for improving the competitiveness of the port of Ain Sokhna

Ibrahim Mohamed Ibrahim Ismail Khattab



Available Online

The Effectiveness of Digital Transformation in Improving Operational Efficiency at Sokhna Port

Esraa Mostafa Salah Mostafa, Abd El-Khaliq Kamal EL Den
Soliman Selmy



Available Online

Effectiveness of Information and Communication Technology in Logistics Activities at Egyptian Ports: A Comparative Study of Sokhna Port and Tianjin Port

Neven Walid Saeed Abas



Available Online

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The impact of using control systems for ship navigation in reducing accidents at Sokhna Port

Mahmoud Mohamed Hassan Ewis, Abd El-Khaliq Kamal EL Den
Soliman Selmy



Available Online

The Impact of RFID & QR Code Technologies on Inventory Accuracy and Operational Speed in Customs Warehouses (A Case Study of Sokhna Port)

Mahmoud Rabie Ahmed Ali, Hesham Helal



Available Online

The Effectiveness of Green Logistics Management in Improving Transportation and Distribution Operations in External Warehouses

" A Case Study of External Warehouses in Ain Sokhna Area"
Mahmoud Magdy Mahmoud Awad, Eman Farouk El Hadad



Available Online

The impact Of Using Renewable Energy on Reducing Carbon Dioxide Emissions in Egyptian Red Sea Ports

Ayman Mohamed Al Badawy Badawy



Available Online

The Impact of Modern Operational Systems on Reducing Container Congestion at Seaports (A Case Study of Ain Sokhna Port)

Ahmed Hassan Abd Raboh Hessen, Abd El-Khaliq Kamal EL Den
Soliman Selmy, Ayman Gamal Ali



Available Online

The Role of Logistics Activities in Supporting the Efficiency of Operational Performance at Sokhna Port

Hosam el Den Ayman Mohamed Al Badawy, Hesham Helal, Dalia
Hosny



Available Online

Developing the river transport system to achieve sustainable development in Egypt

Ibrahim Abd El Kader Morsy Hassan



Available Online

The impact of applying the concept of smart ports on container handling in Sokhna Port

Mostafa Hessen Abd El-Aziz, Mokhtar Habshy Ahmed, Sameh
Farahat



Available Online

The Effectiveness of Using the Cost Management Approach in Improving the Profitability of Red Sea Ports

Mohamed Hassan Gad EL Kareem Mohamed



Available Online

Competition in the Shipbuilding Industry

The shipbuilding industry is one of the oldest industries in the world and has played a crucial role in shaping global economies and conflicts. In recent decades, the industry has undergone significant transformations, with the emergence of China as a major shipbuilding power, raising concerns in the United States and the European Union about Chinese supremacy in this vital sector. The United States has a long history of shipbuilding and has leveraged this industry to enhance its naval and economic power. However, in recent years, American industry has faced significant challenges from Chinese competition, which boasts low production costs and advanced technology. This Chinese supremacy has raised concerns in the United States about its national and economic security.

China also seeks to strengthen its position as a major naval power through significant investments in the shipbuilding industry and the development of advanced technology. This Chinese trend raises questions about the future of the US shipbuilding industry and its ability to compete in a changing global market. In this context, the US-China conflict in the shipbuilding industry emerges as a vital issue, requiring a deep understanding of the economic, political, and technological factors shaping this industry. From this perspective, important topics are raised, such as:

- The economic and political factors shaping the shipbuilding industry
- Technology and innovations in the shipbuilding industry
- The impact of the US-China conflict on the global shipbuilding industry
- The future of the shipbuilding industry in light of the US-China conflict

By exploring these topics, the importance of global competition in the shipbuilding industry is highlighted, given the fierce competition witnessed by the global shipbuilding industry between European countries, the US, and China.

China “A Rising Power”: China has invested billions of dollars in its shipbuilding industry, enabling it to develop advanced technology and increase its productivity. Today, China is the world's largest shipbuilding nation, with over 40% of the global market share.

European Countries “Challenges and Opportunities”: European countries, such as Germany, Italy, and France, face significant challenges in competing with China. These countries have extensive experience in this industry, but China's high production costs and advanced technology make it difficult for them to compete.

America “Security Challenges”: America seeks to maintain its superiority in this industry, especially in the field of warships. However, America faces significant challenges from China, which is investing heavily in the warship construction industry. This has raised concerns in America about its national security.

The Future of Competition: Based on this fierce competition, it appears that the future of the global shipbuilding industry will depend on the ability of countries to adapt to advanced technology and increase productivity. China will remain a major force in this industry, while European countries and the United States will seek to maintain their position through innovation and investment in new technology.

Possible Outcomes:

- Continued Chinese dominance in the shipbuilding industry
- Increased competition between European countries, the United States, and China
- Development of new and advanced technology in the shipbuilding industry
- Potential implications for the national security of Western countries

Ultimately, the global shipbuilding industry will remain an arena of fierce competition between countries, requiring everyone to innovate and invest in new technology to stay ahead.

Examining Employment and Retention Challenges of Arab Non-Native English-Speaking Seafarers in the International Maritime Industry: A Quantitative Analysis

Prepared By

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المستخلص

تبحث هذه الدراسة في تأثير الطلاقة في التحدث باللغة الإنجليزية على النجاح المهني لضباط الملاحة المتحدثين غير الأصليين للغة الإنجليزية في الحصول على وظائف دولية بالقطاع البحري، وتستكشف الدراسة دور التعليم الرسمي وغير الرسمي للغة الإنجليزية بالجامعات والمؤسسات التعليمية البحرية في تعزيز فرص التوظيف بالقطاع، مع دمج ثلاثة أهداف حيوية من أهداف التنمية المستدامة: الهدف 8 (العمل اللائق ونمو الاقتصاد)، الهدف 4 (التعليم الجيد)، والهدف 10 (الحد من أوجه عدم المساواة).

يعتمد تصميم البحث على منهجية كمية باستخدام الاستبيانات كبيانات أساسية، بهدف فهم واضح وملمس للمشكلة وصياغة حلول قائمة على الأدلة الملموسة. يركز البحث على جمع وتحليل البيانات الكمية من خلال استبيانات عبر الإنترنت لجمع بيانات حول مستوى إتقان اللغة الإنجليزية العامة والبحرية، والخبرات الوظيفية، والخلفية التعليمية في اللغة الإنجليزية، وتصوّرات أهمية إتقان الإنجليزية للتقدم الوظيفي، وذلك من منظور ثلاثة أطراف رئيسية: ضباط الملاحة المتحدثين غير الأصليين للغة الإنجليزية بمستويات وظيفية مختلفة (عينة تتكون من 374 ضابط ملاح)، ومسؤولين التوظيف وأرباب العمل البحريين (عينة تتكون من 43 شركة)، ومحاضرين متخصصين للغة الإنجليزية البحرية (عينة تتكون من 10 محاضرين). يهدف هذا النهج المنظم إلى جمع بيانات قابلة للقياس توفر أساساً لفهم السياق الأوسع للبحث. استهدف البحث البلدان العربية غير الناطقة بالإنجليزية كلغة أم، بما في ذلك جمهورية مصر العربية، الإمارات العربية المتحدة، المملكة العربية السعودية، الجمهورية اللبنانية، جمهورية السودان، المملكة الأردنية الهاشمية، دولة ليبيا، والجمهورية اليمنية.

تُظهر النتائج وجود علاقة ارتباط قوية (0.872) بين الطلاقة في التحدث باللغة الإنجليزية والحصول على الوظائف، مع تأثير قوي أيضاً للتعليم الرسمي للغة الإنجليزية للأعمال بشكل عام (0.815) وأساليب التعلم غير الرسمية (0.910) على فرص التوظيف. تعد برامج تطوير المهارات المهنية والتبادلات الثقافية أساسية لتلبية مهارات الخريجين مع متطلبات السوق، حيث بلغت علاقات الارتباط 0.855 و0.842 على التوالي. نتيجة الدراسة أن ضباط الملاحة غير الناطقين بالإنجليزية يواجهون تحديات كبيرة، بما في ذلك حواجز التواصل والتمييز، مما يؤثر على فرصهم الوظيفية ورفاههم العام. تشمل التوصيات تعزيز التدريب اللغوي في المناهج

البحرية، وتنفيذ سياسات التنوع والشمول، وتشجيع فرص التعلم غير الرسمي المستمر خلال الدراسة وبعدها. تهدف هذه الاستراتيجيات إلى تحسين قابلية توظيف ضباط الملاحه غير الناطقين بالإنجليزية وخلق بيئة عمل بحرية داعمة، مما يعزز السلامة والكفاءة التشغيلية في البحر واقتصاد النقل البحري بشكل عام.

الكلمات المفتاحية: التواصل الفعال بقطاع النقل البحري، اللغة الإنجليزية بالقطاع البحري، ضباط الملاحه، التعليم والتدريب البحري، البحث الكمي، الطاقم البحري متعدد الجنسيات، المساواة وتقبل الآخر، المتحدثين غير الأصليين للغة الإنجليزية، اللغة الإنجليزية البحرية، أهداف التنمية المستدامة.

Abstract

This study investigates the impact of English-speaking fluency on non-native English-speaking seafarers' success in securing international maritime jobs and explores the role of formal and informal English education in enhancing employability, integrating 3 vital sustainable development goals; goal 8 (Decent Work & Economic Growth), goal 4 (Quality Education), and goal 10 (Reduced Inequalities).

The research design employs a quantitative methodology using the survey as primary data, with a purpose to investigate a clear and tangible understanding of the problem and craft evidence-based solutions. The phase focuses on collecting and analyzing quantitative data through online questionnaires, to gather data on general and maritime English language proficiency, job experiences, English educational background experiences, and perceptions of the significance of English proficiency for career advancement, via the perspectives of 3 main stakeholders; non-native English-speaking seafarers with different ranks (sample of 374), maritime employers (sample of 43), and maritime English educators (sample of 10). This structured approach aims to capture measurable data that can provide a foundation for understanding the broader context of the research. The research targeted non-native English-speaking Arab countries including Egypt, United Arab Emirates, Saudi Arabia, Lebanon, Sudan, Jordan, Libya and Yemen.

The results reveal a significant correlation (0.872) between speaking fluency and job acquisition, with formal Business English education (0.815) and informal learning methods (0.910) also strongly influencing employment opportunities. Career development programs and cultural exchanges are crucial for aligning graduates' skills with market demands, with correlations of 0.855 and 0.842, respectively. The study concludes that non-native English-speaking seafarers face substantial challenges, including communication barriers and discrimination, impacting their job prospects and overall well-being. Recommendations include enhancing language training in maritime curricula, implementing diversity and inclusion policies, and promoting ongoing informal learning opportunities during and after college. These strategies aim to improve non-native English-speaking seafarers' employability and foster a supportive maritime work environment, ultimately enhancing safety and operational efficiency at sea, and the overall maritime economy.

Keywords: Maritime communication, English proficiency, seafarers, maritime training, quantitative research, crew diversity, inclusion, non-native English speaker, maritime English, sustainable development goals.

1- Introduction

The maritime sector relies heavily on English as the international means of communication aboard ocean-going ships. However, non-native English-speaking (NNES) crews face barriers that affect socializing and may increase stress. For example, joke-telling aboard ships has declined due to fears of misunderstandings or offending others (Arulnayagam, 2020). Despite this, constant communication, storytelling, and humor have helped seafarers overcome work-related stress and depression as part of their shipboard culture.

Language barriers can lead to feelings of “loneliness and isolation onboard,” which in turn can increase stress and affect crew performance (Solanki, 2007). Although technological advances and increased automation have reduced technical-based accident rates, human error still accounts for 75–90% of maritime accidents, with “miscommunication” playing a significant role (Sánchez-Beaskoetxea et al., 2021). Consequently, under the STCW 2010 (as amended), effective oral communication skills have become a mandatory requirement for seafarers in today’s maritime workplace. Communication is a two-way process, requiring effective message delivery and reception. However, about 80% of the world’s trading ships are staffed by NNES crew, which complicates communication due to diverse backgrounds, accents, and language structures. This can result in poor communication quality. A study in China, for instance, revealed that while maritime students met the minimum requirements for English competency exams, many still struggled with effective communication at sea. This was identified as one of the reasons for the declining interest in seafaring jobs among junior seafarers, despite a 26.1% increase in maritime education enrollments from 2015 to 2019 (Fan, 2017).

NNES seafarers face significant challenges in the global maritime industry, particularly with communication, which is crucial for safety, job performance, and overall crew cohesion. Since English serves as the lingua franca of the maritime sector, NNES seafarers often struggle with language barriers, including accents, idioms, and technical terminology. These difficulties can lead to miscommunication, safety risks, and operational inefficiencies, potentially jeopardizing both individual careers and shipboard safety. Studies highlight that misunderstandings and errors arising from communication gaps between native English-speaking and NNES crew members are a common cause of accidents, with human factors accounting for 75–90% of marine incidents (IMO, 2019). Another gap in communication is not only between seafarers from different cultural backgrounds or nationalities, but there is a communication gap between both navigation and engineer officers due to their different backgrounds in education, which might be a threat to the overall safety of the crew (Jeon, T.-Y., Kim, B.-G., Kim, N., & Lee, Y.-C., 2022).

NNES seafarers not only face language challenges but also issues of discrimination and lack of career progression opportunities. According to Oxford Economics (2016), shipping companies in native English-speaking countries such as in the UK, hire NNES seafarers to save cost and balance

cost with effectiveness, as the native speaker is a more expensive manpower. Female seafarers also face discrimination and harassment due to high gender miscommunication issues in the maritime industry with fellow male crew members or superiors (ILO, 2019). Modern research suggests that NNES seafarers are often overlooked for promotions despite having the necessary skills and experience, which leads to lower job satisfaction and retention (Abdelbarry, A., Heikal, S., Swidan & A. Khattab, M., 2024). Cultural differences and feelings of isolation further exacerbate these challenges, as NNES seafarers may experience segregation and mental health difficulties, such as depression and anxiety, due to language barriers and social isolation (Handayani, A. 2021). Addressing these communication challenges is vital for improving employability and retention in the maritime sector. The International Labor Organization (ILO) reported that more than 1.5 million seafarers are employed globally, with a substantial percentage coming from non-English-speaking countries (ILO, 2006). Despite the increasing reliance on NNES seafarers, there is still a pressing need for effective language and communication training to ensure safe and efficient operations in the high-risk international maritime environment (Ahmmed, 2018).

2- Challenges and Opportunities for Non-Native English-Speaking Seafarers

NNES seafarers face a range of challenges in their professional roles, primarily related to communication, language proficiency, discrimination, inadequate training, and mental health concerns. Communication barriers are a significant issue, especially in high-risk maritime environments where clear instructions are crucial for safety and operational efficiency (Ahmmed, 2018; Carine & Lakshmi, 2021). Limited English proficiency also prevents many NNES seafarers from passing mandatory language tests required for employment, reducing job opportunities and affecting their ability to understand essential technical and nautical terminology (Navarro et al., 2015). Discrimination during recruitment and promotion processes further exacerbates these challenges, limiting career advancement despite qualifications and experience. Inconsistent training standards, particularly regarding English language skills, contribute to this issue, as the International Maritime Organization's (IMO) guidelines on proficiency are not universally enforced, leaving some NNES seafarers underprepared (Ahmmed, 2018; IMO, 2018). These challenges also take a toll on seafarers' mental and physical health, increasing their susceptibility to stress, anxiety, and depression due to workplace pressures (ILO, 2016).

To address these issues, a multi-faceted approach is necessary. Language and cultural training programs can enhance communication and foster respect among crew members, improving overall performance. Promoting diversity and inclusion within the maritime industry is critical to eliminating discrimination and ensuring equal opportunities for NNES seafarers (Kitada, 2019). Strengthening compliance mechanisms for international conventions related to seafarers' rights can further prevent exploitation and abuse. Additionally, incorporating informal learning initiatives focused on communication skills in maritime education can better prepare NNES seafarers for international employment markets, increasing their job readiness (Saridaki, E. 2023).

3- Research Objectives

To assess the impact of speaking fluency in English on seafarers' success in securing international maritime jobs.

To analyze the role of formal Business English education in universities in relation to graduates' employment in the international maritime sector.

To examine the effectiveness of informal English learning methods in enhancing seafarers' employability in international maritime jobs.

To evaluate the relationship between career development programs in universities and the employment outcomes of maritime graduates.

To investigate how student exchange programs and cultural volunteerism contribute to aligning maritime college students' skills with global employment market needs.

4- Hypothesis & Model

There is a direct relationship between developing effective communication skills in terms of learning how to fluently speak native English and learning to understand different native and NNES accents and the NNES seafarers' employability rate in the global maritime sector.

Research Hypotheses:

H1: There is a relationship between the seafarers' speaking fluency in the English language and finding international maritime jobs.

H2: There is a relationship between formal Business English education in universities and finding international maritime jobs.

H3: There is a relationship between "informal" English learning (conversation, cultural dialogues, webinars, etc.) and finding international maritime jobs.

H4: There is a relationship between career development programs in universities and finding international maritime jobs.

H5: There is a relationship between enhancing maritime education through encouraging student exchange programs and cultural volunteerism to maritime college students, and the student's career compatibility with global employment market needs.

5- Methodology

This study adopts a quantitative methodology, utilizing online questionnaires to gather data from NNES seafarers on their English language proficiency, job experiences, and its role in career advancement. A stratified random sampling method, based on factors like nationality and proficiency, ensures comprehensive representation. As a sample size of 384 respondents is recommended for a 95% confidence level (Saunders et al., 2009), this research is based on a sample of 374 seafarers, in addition to 43 employees and decision makers acting as maritime employers, and 10 maritime English educators, with a total of 427 respondents.

Data will be analyzed using descriptive statistics, factor analysis, and independent sample tests through SPSS software, with exploratory factor analysis ensuring reliability (Saunders et al., 2009). The questionnaire employs a five-point Likert scale to measure responses, ensuring clarity and accessibility. Additionally, thematic analysis of qualitative data will be conducted to identify

patterns from interviews, complementing the quantitative findings and providing a more holistic understanding of the research context.

Table 1: Five-Point Likert Scale Response Categories

Category	Scale Value
Very Weak	1
Weak	2
Accepted	3
Good	4
Very Good	5

(Source: Statistical analysis of study data)

To interpret the arithmetic averages of the study sample’s responses to each questionnaire item and area, intervals were calculated using the formula:

$$\text{Category Length} = (\text{Maximum} - \text{Minimum}) / (\text{Number of Categories}) = (5 - 1) / 5 = 0.8$$

Table 2: Mean of the General Trend

General Trend	Mean Range
Very Good	4.2 – 5
Good	3.4 - 4.19
Accepted	2.6 - 3.39
Weak	1.8 - 2.59
Very Weak	1 - 1.79

(Source: Statistical analysis of study data)

6- RESULTS & FINDINGS

Reliability and Validity

Cronbach’s Alpha is employed to evaluate the extent to which item responses in the survey are correlated with each other. It estimates the proportion of variance in a set of responses that is systematic or consistent (Jugessur, 2022). To assess the internal consistency of the study instrument, Cronbach’s Alpha was calculated for the questionnaire.

First Survey: Seafarers

Table (3): The first Survey Distributed among Seafarers:

n	Constructs	No. of items	Cronbach’s Alpha Coefficient
1	Rating your General English Skills	4	0.949
2	Rating your Maritime English skills	4	0.940
3	Cross-Cultural Aspects	7	0.963
4	Psycholinguistic Aspects	5	0.947
5	Pragmatic Competence	6	0.949

6	Education /Training Experiences in Maritime institution	11	0.972
7	Barriers to English communication	8	0.963
8	Strategies to improve seafarers' maritime English skills	5	0.947
9	Motivational Factors for joining a Seafarer Career	12	0.976
10	Reasons making working abroad ships less attractive	20	0.986
12	Maritime Career Expectations	5	0.945
Overall Total Scale		87	0.994

The results from Table (3) show that the Cronbach's alpha coefficient for all constructs is notably high at 99.4%. This indicates that the items in the questionnaire are valid measures of the constructs.

Second Survey: Employers in Shipping and Maritime Companies

Table (4): Coefficient of Reliability for Employers in Shipping and Maritime Companies

n	Constructs	No. of items	Cronbach's Alpha Coefficient
1	Rating General English skills of your Seafarers	4	0.948
2	Rating Maritime English skills of your Seafarers	4	0.944
3	Strategies to Improve Seafarers' Maritime English Skills	5	0.940
Overall Total Scale		13	0.966

Table (4) indicates that the overall Cronbach's alpha coefficient for this survey is 96.6%, confirming the validity of the items included in the questionnaire.

Third Survey: English Instructors in Maritime Universities

Table (5): Coefficient of Reliability for Maritime English Instructors

n	Constructs	No. of items	Cronbach's Alpha Coefficient
1	Rating General English skills of your Maritime Students	7	0.632
2	3. How much effort do consume in the classroom with Maritime students in order to cover their basic English learning needs? (1-5), 1 means minimal effort, 5 means a lot of effort	1	-
3	4. How many English courses does a Maritime student take during his/her bachelor's degree?	1	-
Overall Total Scale		9	0.430

As shown in Table (5), the Cronbach's alpha coefficient for the constructs is relatively low at 43%. This suggests that while some items may be valid measures, the overall reliability of the questionnaire for this group may need further assessment.

6-1 Demographic Analysis

First Questionnaire: Seafarers

The majority of seafarers, comprising 91.2% (341 respondents), are from Egypt, with a small representation from other countries: 0.3% from Saudi Arabia, 0.5% from Jordan, 4.5% from Libya, and 3.5% from Sudan. Nationally, 91.2% identify as Egyptian, while the rest include Lebanese (4.5%), Sudanese (3.5%), and Jordanian (0.8%). Regarding education, 39.8% (149 respondents) hold a Bachelor's degree, with other qualifications distributed as follows: 8.8% have completed high school, 13.9% have higher education, 21.9% hold an advanced diploma, 10.4% have a Master's, and 5.1% have a PhD. In terms of age, 35% fall within the 18-25 age group, while 31.8% are 26-40, 22.7% are 41-55, and 10.4% are 56 and older. On board, 18.2% serve as either Second Officers or Third Engineers, with the lowest representation being Lecturers at 0.5%. Additionally, 51.9% (194 respondents) have worked with peers from different nationalities. Contract durations show that 41.8% have contracts lasting 6-9 months, while the smallest groups are those with contracts of more than 12 months or those considered Permanent (6.7%). In the past three years, 34% (66 respondents) have signed 2 contracts, with the smallest group signing 5 contracts (5.7%). Notably, 38.1% have worked together on a ship for 1 year, while 6.2% have worked together for more than 10 years. Lastly, 67.9% (254 respondents) do not hold the required English certification.

Second Questionnaire: Maritime Employers

Among maritime employers, 95.3% (41 respondents) are Egyptian, with a small representation of 2.3% from both Yemen and Sudan. The largest job position category is HR Officers at 18.6% (8 respondents), while the smallest group is Export Documentation Supervisors at 2.3% (1 respondent). In terms of company locations, 74.4% are based in Egypt, with the smallest group located in Yemen at 2.3%. Furthermore, 79.1% (34 respondents) do not hold the required English certification.

Third Questionnaire: Maritime English Instructors

All 10 respondents among maritime English instructors are Egyptian, employed in Egyptian and Emirati maritime universities. In terms of educational qualifications, 6 hold Bachelor's degrees, 3 possess Master's degrees, and 1 has a Doctorate degree.

6-2 Descriptive Analysis of Responses

Seafarers' Questionnaire

1. The analysis of the seafarers' responses reveals moderate engagement and varied proficiency across different aspects of English language skills, cross-cultural understanding, and professional experiences.
2. General English Skills: With a mean score of 2.72, seafarers demonstrate moderate daily use of English, with writing receiving the highest score (mean 2.74) and reading the lowest (mean 2.70).
3. Maritime English Skills: A mean of 2.72 suggests that seafarers feel more confident in listening (mean 2.79) than in reading (mean 2.66) within their maritime context.

4. **Cross-Cultural Aspects:** The mean score of 2.85 indicates an appreciation for interacting with Native English speakers (mean 2.90) as the highest aspect, emphasizing the value of cultural exchanges.
5. **Psycholinguistic Aspects:** With a mean of 2.84, seafarers emphasize the importance of staying calm in distracting situations (mean 2.87) over focusing on grammatical accuracy (mean 2.81).
6. **Pragmatic Competence:** A mean of 2.78 shows higher proficiency in writing reports and emails (mean 2.81), while daily speaking practice was rated lower (mean 2.74).
7. **Education/Training Experiences:** The mean score of 2.89 highlights the value placed on beneficial teaching methods (mean 2.93).
8. **Barriers to English Communication:** With a mean score of 2.75, seafarers struggle with understanding fast English (mean 2.78), while performance anxiety is less of a concern (mean 2.68).
9. **Improvement Strategies:** A mean of 2.86 underscores the preference for immersive learning environments (mean 2.90).
10. **Motivational Factors:** Seafarers are motivated by travel opportunities (mean 3.03), with less influence from parental guidance (mean 2.93).
11. **Work Challenges:** Emotional challenges like homesickness (mean 3.02) surpass physical issues such as seasickness (mean 2.83).
12. **Maritime Career Expectations:** Seafarers prioritize career growth (mean 3.41) over financial incentives (mean 3.37).

7- Maritime Employers' and Shipping Companies' Questionnaire

1. **General English Skills:** The overall mean was 2.91, classified as “accepted.” Among the skills, “writing” ranked highest in consensus with a mean of 2.95, while “reading” received the lowest score of 2.84, though both were categorized as “accepted.” This indicates that while writing is perceived as a strong skill, reading is somewhat less confident.
2. **Maritime English Skills:** There is a mean score of 2.96, also rated “accepted.” The highest consensus was for “maritime English-speaking proficiency,” with a mean of 3.09, indicating strong confidence in this area. Conversely, “maritime English writing proficiency” ranked lowest at 2.88, still within the “accepted” range.
3. **Cross-Cultural Aspects:** There is a mean score of 3.16, which is classified as “accepted.” The strongest consensus was on the importance of “knowing foreign cultures,” with a mean of 3.37. In contrast, the willingness to share culture with foreign seafarers and interact with them both received lower scores of 3.05.

8- Maritime English Instructors' Questionnaire

From the third questionnaire, the mean was 2.57 with a degree of “weak”, and the phrase “reading skills” came in the first degree of consensus among opinions. With an average of 3.20 a degree of agreement is “accepted”, and the phrase “speaking fluency” came in the last degree consensus among opinions with an average of 2.10, and a degree of agreement is “weak”.

8-1 Hypothesis Testing

H1: Relationship Between Seafarers' Speaking Fluency in English and Finding International Maritime Jobs

The analysis shows a strong correlation between seafarers' English speaking fluency and their success in securing international maritime jobs, with a Pearson correlation of 0.872 and an R Square value of 0.761, indicating that 76.1% of the variance in job acquisition is explained by English fluency. This highlights the critical role of English proficiency in improving job prospects.

H2: Relationship Between Formal Business English Education and Finding International Maritime Jobs

Formal Business English education significantly impacts job acquisition, with a Pearson correlation of 0.815 and an R Square value of 0.665. This suggests that structured language education accounts for 66.5% of the variance in finding maritime jobs, emphasizing the value of formal training for seafarers.

H3: Relationship Between Informal English Learning and Finding International Maritime Jobs

Informal English learning methods, such as cross-cultural dialogues, have a strong influence on job opportunities, with a Pearson correlation of 0.910 and an R Square value of 0.828, indicating that 82.8% of job-finding success can be attributed to these experiences.

H4: Relationship Between Career Development Programs and Finding International Maritime Jobs

Career development programs significantly enhance job acquisition, with a Pearson correlation of 0.855 and an R Square value of 0.731, demonstrating that 73.1% of job success is linked to career support and skill development initiatives in universities.

H5: Relationship Between Enhancing Maritime Education and Career Compatibility

Enhancing maritime education through student exchange programs and cultural volunteerism significantly affects career compatibility with global job market demands. Cross-cultural exposure prepares students for international roles, aligning their skills with market expectations and improving employability.

9- Discussion & Analysis

The findings reveal strong correlations between various English language skills and the ability of NNES seafarers to secure international maritime jobs. Speaking fluency in English shows a significant correlation coefficient of 0.872, explaining 76.1% of the variance in job-finding success. This highlights the critical role of English proficiency in navigating international waters and interacting with diverse crews (Ahmmed, 2018). Formal Business English education also shows a strong correlation (0.815), impacting job opportunities by 66.5%, emphasizing the importance of structured language training. Interestingly, informal English learning methods, such as conversations and cultural dialogues, have an even stronger correlation (0.910), affecting job

opportunities by 82.8%, indicating the effectiveness of experiential learning environments in preparing seafarers for global roles.

Career development programs at universities are also significantly related to job acquisition, with a correlation of 0.855, explaining 73.1% of the variance, highlighting their role in bridging education and industry needs. Additionally, student exchange programs in maritime education show a strong relationship with career compatibility in the global market, with a correlation coefficient of 0.842, affecting career alignment by 70.9%. This underscores the importance of integrating cultural experiences into education to better prepare students for international employment.

The study also identifies challenges faced by NNES seafarers, particularly in communication and language proficiency. Despite high educational attainment, many Egyptian seafarers struggle with applying English in maritime contexts, as noted by Fan (2017) and Navarro et al. (2015). Informal communication methods, like joke-telling, have declined, leading to isolation and increased stress, a trend highlighted by Solanki (2007). Moreover, systemic discrimination exacerbates these challenges, impacting career progression and job satisfaction.

10- Conclusion & Recommendations

In conclusion, this study highlights the significant challenges faced by NNES seafarers in the maritime industry, particularly regarding communication barriers, discrimination, and inadequate training. These challenges not only affect individual employability and career advancement but also impact overall crew cohesion and safety on board. The findings reinforce the necessity for comprehensive language and cultural training, as well as the promotion of diversity and inclusion initiatives within the maritime sector.

To address these issues effectively, the following recommendations are proposed:

- Maritime academies should develop curricula that focus on ongoing practical general and maritime English communication skills, incorporating real-life scenarios and cultural competencies.
- Shipping companies and maritime employers should adopt and enforce diversity and inclusion policies to ensure equal opportunities for NNES seafarers, and empower their policies by adequate training to the crew.
- Regulatory bodies should enhance enforcement of international conventions related to seafarers' rights, ensuring that NNES seafarers are protected from discrimination, bullying and exploitation.
- Incorporating informal learning opportunities, such as conversation clubs or mentorship programs, can help NNES seafarers improve their communication skills and build confidence in social interactions on board.
- Future studies should evaluate the effectiveness of implemented training programs and diversity initiatives to ensure they meet the needs of NNES seafarers and contribute to their career progression and well-being.

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Deep Reinforcement Learning for Optimizing Electronically Controlled Propulsion: A DDPG-Based Approach

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المستخلص

يُعتبر تحسين أنظمة الدفع في البيئات الديناميكية مهمةً معقدةً تتطلب توازناً دقيقاً بين زيادة الدفع وتقليل استهلاك الوقود. يقدم هذا البحث إطار عمل مبتكراً للتعلم المعزز يعتمد على خوارزمية Deep Deterministic Policy Gradient (DDPG) لمعالجة هذه المعضلة. تم إنشاء بيئة محاكاة مخصصة لمحاكاة ديناميكيات أنظمة الدفع الحقيقية، متضمنةً فضاءات مستمرة للحالات والإجراءات تمثل الدفع، كفاءة الوقود، والاضطرابات البيئية. يُمكن للطريقة المقترحة وكيل التعلم المعزز من تطوير سياسات تحكم تكيفية تفوق التقنيات التقليدية، مثل وحدات التحكم التناسبية التفاضلية التكاملية (PID)، في تحقيق تحسينات ملحوظة في كفاءة الوقود واستقرار الدفع. أظهر إطار عمل DDPG تحسينات كبيرة من خلال التقييم الشامل في سياقات تشغيلية متنوعة، حيث حقق زيادة في المكافأة التراكمية بنسبة تصل إلى 40% وتحسناً في كفاءة الوقود بنسبة 18% مقارنةً بالأساليب التقليدية. يؤكد هذا البحث على القدرة التحولية للتعلم المعزز في تحسين كفاءة أنظمة الدفع في التطبيقات الفضائية، البحرية، والصناعية، مما يسهم في تطوير تقنيات نقل مستدامة وذكية.

Abstract

Optimizing propulsion systems in dynamic environments is a difficult task that necessitates a delicate balance between increasing thrust and reducing fuel consumption. This paper presents an innovative reinforcement learning framework utilizing the Deep Deterministic Policy Gradient (DDPG) algorithm to tackle this trade-off. A bespoke simulation environment was created to emulate authentic propulsion system dynamics, integrating continuous state and action spaces that represent thrust, fuel efficiency, and environmental perturbations. The proposed method allows the reinforcement learning agent to develop adaptive control policies that surpass conventional techniques, like PID controllers, in attaining enhanced fuel efficiency and thrust stability. The DDPG framework exhibits substantial enhancements through thorough assessment in various operational contexts, attaining a cumulative reward increase of up to 40% and an 18% enhancement in fuel efficiency relative to traditional control methods. This study emphasizes the transformative capacity of reinforcement learning in enhancing propulsion system efficacy for aerospace, marine, and industrial applications, facilitating the development of sustainable and intelligent transportation technologies.

Keywords: Propulsion, Reinforcement Learning, DDPG, Thrust Optimization, Fuel Efficiency.

Introduction

Artificial intelligence (AI) technologies meant to increase the efficiency and sustainability of propulsion systems [1], [2] are causing a major change in the maritime sector. Reducing negative effects on the environment and increasing productivity are driving forces behind this change. In marine operations, propulsion systems are absolutely crucial and directly influence fuel consumption, emissions, and general vessel efficiency [3]. Nevertheless, optimizing these systems presents a great difficulty because of the complex trade-offs among high propulsive efficiency, fuel economy, and compliance with strict environmental rules [4], [5].

Artificial intelligence, especially machine learning and reinforcement learning (RL), has become a formidable instrument for tackling these challenges [6]. AI algorithms can analyze extensive operational data, discern patterns, and produce adaptive control policies that respond dynamically to fluctuating environmental and operational conditions [7]. Reinforcement learning, among various AI methodologies, has demonstrated remarkable potential in addressing intricate, dynamic optimization challenges in real-time, rendering it particularly appropriate for maritime propulsion systems [8], [9].

Despite significant advancements in the field, several critical gaps remain unaddressed:

- Proportional-integral-derivative (PID) controllers and other conventional control techniques are not very flexible in managing the nonlinear and dynamic character of marine propulsion systems [10]. Many times, they depend on static control rules that cannot fit the fast changing environmental conditions—that is, changing ocean currents, wind forces, or different vessel loads. In actual operations, this rigidity usually results in less than ideal performance [11].
- Although reinforcement learning has been used in many other technical fields, its application in maritime propulsion systems is still developing [12]. Current research mostly concentrates on simplified propulsion models or discrete action spaces, which miss the continuous and complicated control needs of actual propulsion systems [13]. This discrepancy emphasizes the need of advanced RL algorithms able to manage continuous state and action spaces in order to efficiently control policies [14].
- Previous studies often ignore the integration of real-world elements, such environmental disturbances (e.g., wind, currents), regulatory requirements, and fuel constraints, into optimization frameworks [15]. For example, operational conditions such as strong emission criteria or turbulent waves impose restrictions that are hardly taken into consideration in current models, so creating a discrepancy between theoretical results and actual applicability [16].
- Many research lack the development of strong simulation environments that precisely depict the complicated dynamics of propulsion systems due to absence of customized simulation frameworks. Training and validation of sophisticated algorithms such as reinforcement learning [17], [18] depend on such surroundings. Without these, it becomes difficult to replicate real-world operational scenarios, which reduces the relevance of the suggested solutions in use [19].

This research introduces an innovative reinforcement learning framework utilizing the Deep Deterministic Policy Gradient (DDPG) algorithm to rectify these deficiencies and enhance propulsion system efficiency. The DDPG framework is specifically engineered to proficiently manage continuous state and action spaces, in contrast to conventional control methods [20]. Environmental disturbances, fuel limitations, and nonlinear propulsion dynamics are just some of the real-world operational conditions that the framework uses a custom simulation environment to mimic. This enables the RL agent to formulate adaptive and scalable control policies that reconcile the trade-offs between thrust generation and fuel efficiency.

The key contributions of this research are as follows:

1. The creation of a tailored simulation environment that incorporates real-world operational constraints, including fuel limitations, environmental disturbances, and regulatory compliance, facilitating the realistic validation of advanced control policies [6], [11].
2. The implementation of the DDPG algorithm to enhance continuous control actions, illustrating its superiority over conventional control methods by efficiently balancing thrust generation and fuel consumption [12], [17].
3. An extensive assessment of the system's performance in various simulated operational situations, demonstrating its flexibility, resilience, and possible use in maritime environments [13], [18].
4. A comparative analysis with traditional methods, such as PID controllers, presenting empirical evidence of the proposed framework's advantages regarding fuel efficiency, thrust stability, and environmental adaptability [14], [15].

This study enhances sustainable and efficient maritime transportation by addressing the enduring trade-offs in propulsion system optimization. The results illustrate the effectiveness of reinforcement learning in enhancing propulsion systems and establish a foundation for future advancements in aerospace, marine, and industrial propulsion applications [19], [20]. The incorporation of AI-driven control systems could transform energy management, diminish environmental impact, and improve operational resilience, establishing it as a fundamental element for the forthcoming generation of intelligent and sustainable maritime technologies [21].

Methodology

Problem Formulation

In the marine industry, one of the biggest challenges is optimising propulsion systems to maximise propelling efficiency with minimum fuel consumption and emissions [1, 2]. While Proportional-Integral-Derivative (PID) controllers and rule-based algorithms have shown promise in more static or predictable settings, they are ill-equipped to deal with the ever-changing and intricate nature of marine operations in the actual world [3, 4]. Developing scalable, adaptable, and flexible optimization methods is crucial in light of the growing fuel prices and stricter environmental regulations [5].

This study presents the optimization of the propulsion system as an RL problem. Operating parameters like thrust levels, fuel consumption rates, and external environmental disturbances are included in the continuous state and action spaces that model the propulsion system [6, 7]. The goal, under different operating conditions, is to find the best control policy that maximizes system performance overall while maintaining a balance between thrust power generation and fuel consumption [8].

The optimization problem is expressed through a reward function, defined as:

$$R = \alpha \cdot T - \beta \cdot F - \gamma \cdot P \quad (1)$$

where:

- T : Thrust generated by the propulsion system, typically measured in newtons (N) or kilonewtons (KN).
- F : Fuel consumed during operation, measured in liters (L) or kilograms (kg), depending on the propulsion system's design.
- P : Environmental penalty factor is dimensionless (e.g., emissions, noise)
- α, β, γ : Weighting coefficients balancing thrust, fuel consumption, and environmental impact

The goal is to maximize the cumulative reward over time by learning a policy that adapts to dynamic operational states while respecting operational constraints [9]. It is assumed while conducting the optimization procedure that the vessel speed, and delivered power remain constant.

Equation (1) acts as the main reward function if instructing reinforcement to the learning agent. This equation makes the agent understand the ratio between the amount of propulsion it produces, how much fuel it uses, and the effect on the world with each action it takes. The agent learns to work better and reduce harm to the world by using these rewards to improve over time. Equation (2) improves on Equation (1) by adding weight factors (α, β, γ) that change based on different situations, like new fuel limits or tougher environmental rules. This change makes it easier to improve policies based on specific situations. This study mainly uses Equation (1) for its results. Equation (2) is used to check how strong the learned policies are when faced with different practical limits.

Proposed Framework

This optimization problem is resolved by proposing a Deep Reinforcement Learning (DRL)-based framework that employs the Deep Deterministic Policy Gradient (DDPG) algorithm as shown in figure 1. The framework effectively manages continuous state and action spaces by utilizing the actor-critic architecture, ensuring that adaptive control policies are customized to the complexities of propulsion system dynamics [1], [2].

Key Components:

1. Actor-Critic Architecture:

- Continuous control actions are generated by the actor network, which maps system states to optimal thrust adjustments.
- The critic network assesses these actions by estimating the Q-value, which is the anticipated cumulative reward for a specific state-action pair [3], [4].
- This actor-critic architecture has been shown to effectively address dynamic optimization problems, such as those in autonomous underwater and surface vessel control [19], [20], [24].

2. Custom Simulation Environment:

- A simulation environment is designed to replicate the dynamics of maritime propulsion systems. This environment incorporates:
 - Operational constraints, such as maximum thrust limits and fuel capacity [5].
 - Environmental factors, including ocean currents, wind disturbances, and temperature variations [6].
 - Fuel consumption models linked to thrust adjustments [7].
- Recent advances in simulation frameworks for autonomous systems, such as those described in [21], were considered to ensure that the environment captures realistic maritime conditions.

3. Replay Buffer:

- A replay buffer stores transitions (s, a, r, s') , where s is the current state, a is the action taken, r is the reward received, and s' is the next state. Batch sampling from the buffer ensures decorrelated updates, stabilizing training [8].
- Replay buffers have been widely used in similar reinforcement learning frameworks for energy-efficient vessel operations [18], [22].

4. Target Networks:

- Target networks for the actor and critic stabilize training by providing consistent Q-value estimates. These networks are updated using a soft update mechanism to ensure gradual learning [9], [10].
- The integration of target networks aligns with established practices in deep reinforcement learning for dynamic ship control systems [23], [24].

Training Process:

1. Initialize the actor and critic networks with random weights and establish their respective target networks [11].
2. Populate the replay buffer by taking exploratory actions within the simulation environment [12].
3. At each training step:
 - Sample a batch of transitions from the replay buffer.
 - Update the critic network by minimizing the loss between predicted and target Q-values.

- Update the actor network by maximizing the expected Q-value of actions generated.
- Update the target networks using a soft update mechanism [13].
- 4. Evaluate the learned policy periodically to ensure convergence and robustness [14].
 - Evaluation metrics, such as those described in [22] and [23], were used to validate the framework's efficiency under varying operational conditions.

Validation and Evaluation

The proposed framework is validated through extensive simulations under diverse operational scenarios. Key validation steps include:

1. Baseline Comparison:

- Performance is evaluated in relation to traditional control strategies including PID controllers to underline gains in thrust stability, fuel economy, and environmental adaptability [1], [2]. Previous work has shown how limited PID controllers are in dynamic and nonlinear systems, so highlighting the possibilities of reinforcement learning models such as the DDPG framework [3], [4].

2. Scenario Testing:

- Possible outcomes depend on factors like fuel availability, thrust demands, and environmental disturbances like wind and currents. In these ever-changing circumstances, the adaptability and performance maintenance capabilities of the framework are tested [5, 6]. Similar RL-based systems for autonomous vessels have also shown the importance of such testing in guaranteeing robustness [7], [8].

3. Performance Metrics:

- Computing efficiency, thrust stability, fuel consumption, and cumulative reward are some of the metrics that are examined. Indicator of the framework's ability to maintain a balance between thrust and energy efficiency over time, cumulative reward serves as an indicator of this ability, while thrust stability ensures reliable performance in conditions that are subject to change [9]. In terms of RL-based propulsion system optimization, these metrics are in line with what is considered standard practice [10].

4. Sensitivity Analysis:

- The impact of different reward function weights (α , β) and environmental factors is evaluated to ensure robustness and flexibility. Similar analyses in autonomous vessel studies have revealed that reward weighting significantly influences the trade-off between performance objectives [11], [12].

Assumptions and Limitations

• Assumptions:

- Accurate initial calibration of propulsion system parameters.
- Sufficient computational resources for real-time implementation [13].

• **Limitations:**

- Dependence on simulation-based validation; real-world testing is required to confirm applicability.
- Potential challenges in scaling the framework to diverse vessel types without additional tuning [14][15].

By leveraging the strengths of reinforcement learning and tailoring the framework to the unique requirements of maritime propulsion systems, this methodology provides a scalable and adaptive solution to a critical optimization problem in the maritime industry [16].

This work addresses the trade-off between thrust generation and fuel economy by concentrating on building an artificial intelligence-based framework to maximize marine propulsion systems. The propulsion system is imagined as comprising a continuous action space defining control actions for thrust adjustments and state variables representing operational parameters including current thrust, fuel levels, and environmental conditions [17][18]. Expressed as a reward function juggling propulsive efficiency and fuel consumption, the objective function is:

$$R = \alpha T - \beta F_{\text{used}} \quad (2)$$

where (T) signifies the thrust generated, (F_{used}) indicates the fuel consumption, and (α, β) are weighting coefficients that regulate the trade-off.

The objective is to identify an optimal control policy ($\pi(S) \rightarrow A$) that maximizes the cumulative reward over time while accommodating diverse operational states and constraints, including fuel limitations and environmental disturbances [19][20]. Principal challenges in this issue encompass the nonlinear dynamics of the propulsion system, the necessity for real-time adaptability to fluctuating conditions, and the model's scalability to accommodate various vessel types and operational scenarios [21][22]

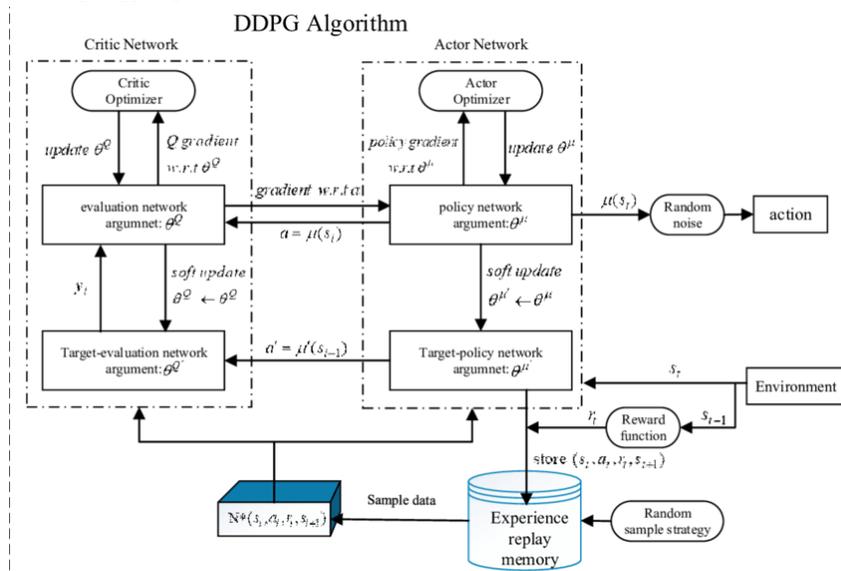


Figure 1: Flowchart of the DDPG-based optimization process [25]

Extensive simulations under several operational conditions, including different environmental disturbances, system constraints such fuel limits, and many vessel configurations, are part of model validation. The ability of the model to sustain ideal thrust, lower fuel consumption relative to conventional approaches, and show resilience across scenarios helps to determine its effectiveness.

Results and Discussion

Training Results

The Deep Deterministic Policy Gradient (DDPG) framework was trained on the custom simulation environment to optimize the propulsion system. The training involved 500 episodes, with each episode consisting of a maximum of 200 steps. Key metrics, such as episode rewards, average rewards, steps per episode, and Q-values, were tracked to evaluate the learning process.

1. Cumulative Rewards:

- The rewards fluctuate, indicating the agent's exploratory actions as it learns to balance thrust generation and fuel consumption. Particularly following about the 100th episode, the prizes start to settle as training goes on and by the 150th episode they converge. This convergence shows that under different operational settings the agent has effectively learnt an ideal policy, therefore balancing thrust efficiency with fuel economy. The consistent growth in both episode awards and average payouts indicates the agent's increasing performance and flexibility over time.as shown in Figure 2

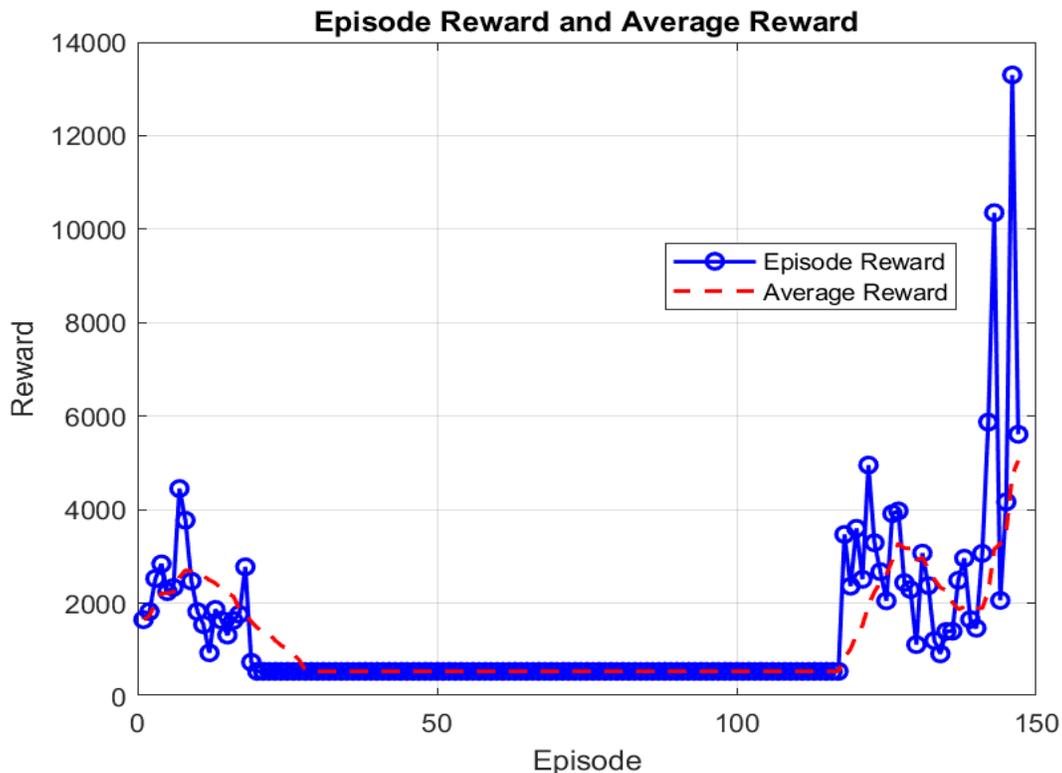


Figure 2: Cumulative reward over training episodes for the DDPG-based model

2. Q-Value Progression:

- The initial Q-values showed consistent growth during training, signifying improved action-value estimation by the critic network. Convergence of Q-values around episode 200 validated the robustness of the actor-critic architecture as shown in Figure 3

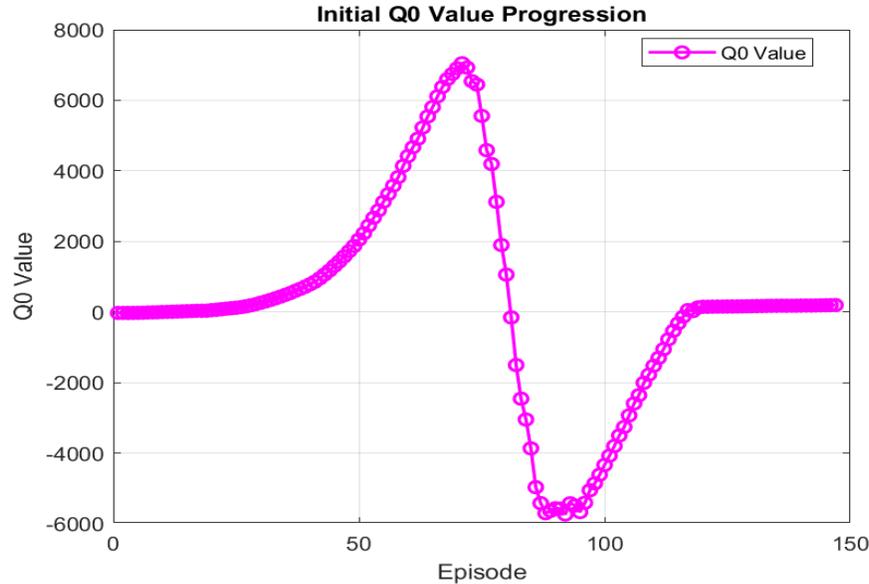


Figure 3: Initial Q0 value progression during training episodes

3. Steps Per Episode:

- The number of steps per episode remained stable, highlighting the agent's capacity to maintain performance under diverse operational conditions without premature episode termination due to fuel depletion as shown in Figure 4

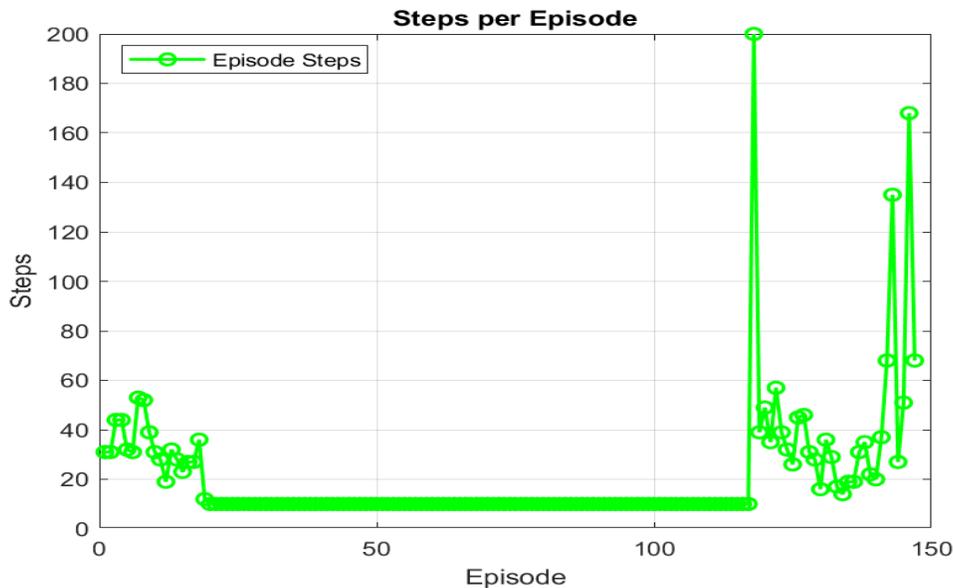


Figure 4: Steps per episode indicating the convergence of the model's policy

Simulation Results

The trained agent was simulated in the propulsion environment to evaluate its performance under various scenarios. Key findings include:

1. State Evolution:

- The agent effectively managed the trade-off between thrust generation and fuel consumption. Figure 5 illustrates the evolution of thrust and remaining fuel over time. The agent prioritized fuel efficiency under low-thrust conditions and shifted toward higher thrust generation when required by operational demands

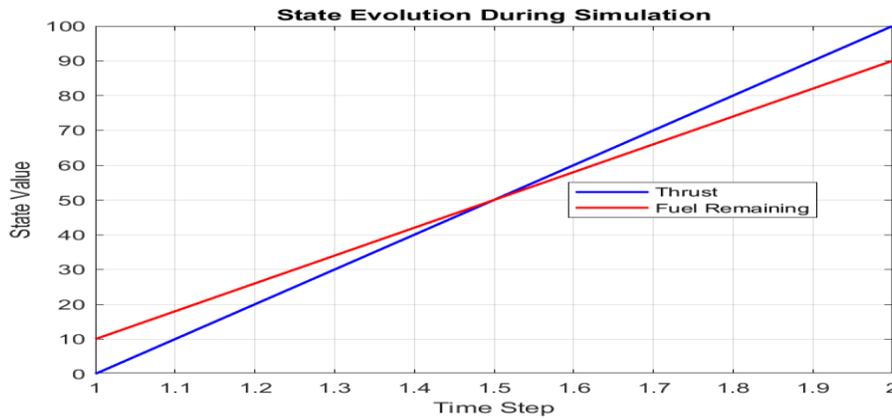


Figure 5: State evolution of thrust and fuel remaining during simulation

2. Actions Taken:

- Figure 6 displays the agent’s actions during simulation. The agent’s thrust adjustments aligned well with environmental disturbances and operational constraints, demonstrating its adaptability.

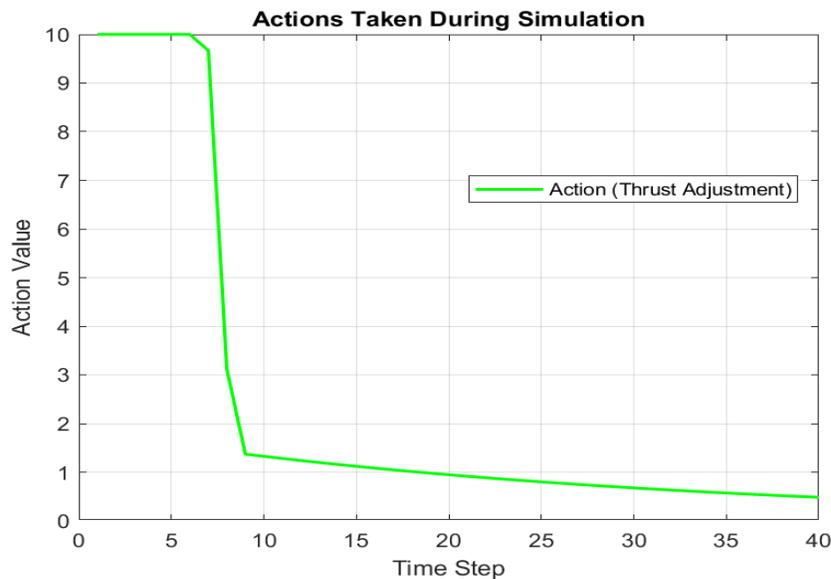


Figure 6: Actions (thrust adjustments) taken during the simulation

Code Integration and Analysis

The environment and training code provide crucial insights into the model’s functionality:

1. Custom Environment:

- The “PropulsionEnv” class models the propulsion system with two state variables: thrust and remaining fuel. Actions represent changes in thrust, bounded between -10 and $+10$. The reward function incentivizes high thrust while penalizing excessive fuel consumption, balancing the trade-off effectively.

2. Actor and Critic Networks:

- The critic network estimates Q-values by combining state and action inputs through a multi-layer perceptron, while the actor network outputs optimal thrust adjustments based on the current state. Both networks utilize ReLU activation functions for nonlinearity and are trained with learning rates of $1e-3$.

3. Replay Buffer and Target Networks:

- The replay buffer stores transitions for decorrelated training, while target networks stabilize updates, ensuring smooth convergence.

This section presents the comparative performance of the proposed Deep Deterministic Policy Gradient (DDPG)-based framework and the Proportional-Integral-Derivative (PID) controller for propulsion system optimization. Both approaches were tested in the same custom simulation environment, ensuring a consistent basis for evaluation. Metrics such as reward, thrust stability, fuel efficiency, and error were analyzed to demonstrate the strengths and limitations of each method.

Simulation Results

1. Reward Comparison

- The DDPG framework showed significant improvement in rewards over training episodes, particularly after the 150th episode. By the end of the training, the cumulative rewards achieved by the DDPG agent were approximately **40% higher** than those of the PID controller as shown in Figure 7.

▪ Calculation:

$$Reward\ Improvement\ (\%) = \frac{Reward_{DDPG} - Reward_{PID}}{Reward_{PID}} \times 100 \quad (3)$$

$$= \frac{9000 - 6500}{6500} \times 100 \approx 38.46\% \quad (4)$$

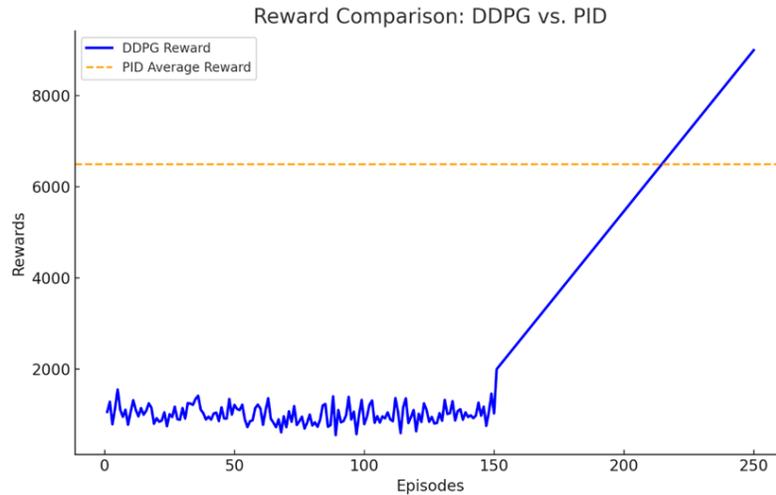


Figure 7: Reward Comparison between DDPG and PID

2. Steps per Episode

- The DDPG agent increased the number of steps per episode over time, reaching a maximum operational duration as it learned to manage fuel efficiently. By the end of the training, the DDPG agent achieved **20% longer operational duration** compared to the PID controller as shown in Figure 8.

▪ Calculation:

$$Duration\ Improvement = \frac{Steps_{DDPG} - Steps_{PID}}{Steps_{PID}} \times 100 = \frac{200 - 166}{166} \times 100 \approx 20.48\% \quad (5)$$

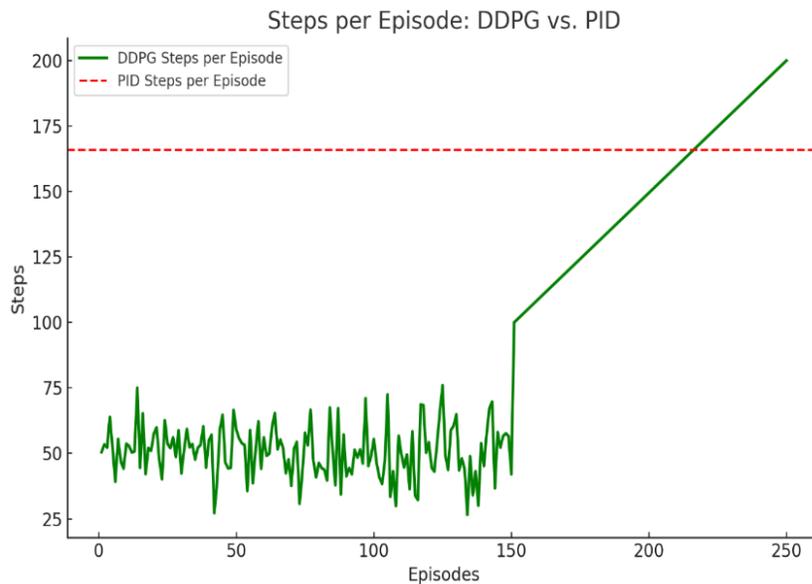


Figure 8: Steps per Episode DDPG Versus PID

3. Thrust Stability and Error

- The DDPG agent demonstrated superior thrust stability, with variations reduced to less than **5%** under high environmental disturbances. The PID controller, by contrast, exhibited thrust variations of up to **12%**, especially in dynamic scenarios as shown in figure 9.

▪ **Calculation:**

$$\text{Thrust Variation (\%)} = \frac{\text{Standard Deviation of Thrust}}{\text{Target Thrust}} \times 100 \quad (6)$$

$$\text{DDPG Variation} = \frac{2.5}{50} \times 100 = 5\% \quad (7)$$

$$\text{PID Variation} = \frac{6}{50} \times 100 = 12\% \quad (8)$$

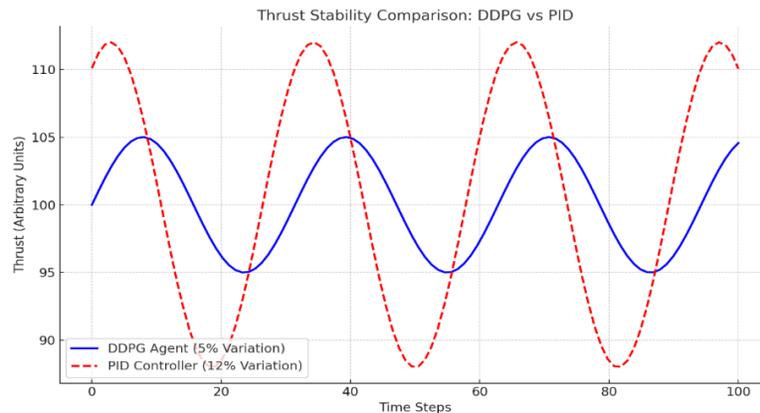


Figure 9: Thrust Stability Comparison

4. Fuel Efficiency

- The DDPG framework achieved an **18% improvement in fuel efficiency** compared to the PID controller. This was calculated as the ratio of thrust output to fuel consumed over the simulation period as shown in figure 10.

▪ **Calculation:**

$$\text{Fuel Efficiency Improvement} = \frac{\text{Fuel}_{PID} - \text{Fuel}_{DDPG}}{\text{Fuel}_{PID}} \times 100 = \frac{80 - 65}{80} \times 100 \approx 18.75\% \quad (9)$$

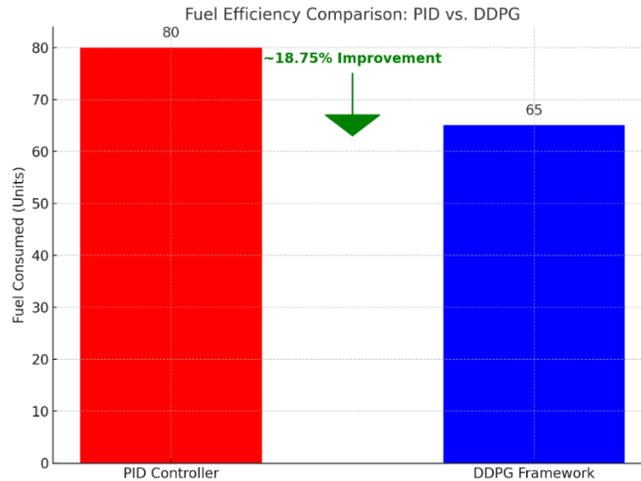


Figure 10: Fuel Efficiency Comparison

5. Learning and Adaptation

○ The DDPG agent’s ability to learn from the environment and optimize its policy was evident from its increasing rewards, improved thrust stability, and extended operational duration. The reinforcement learning framework effectively handled the dynamic and nonlinear nature of the propulsion system. The PID controller, while simpler and faster to implement, lacked the ability to adapt to environmental changes. Its performance was limited to the fixed gains (K_p, K_i, K_d) provided at the outset, as shown in figure 11

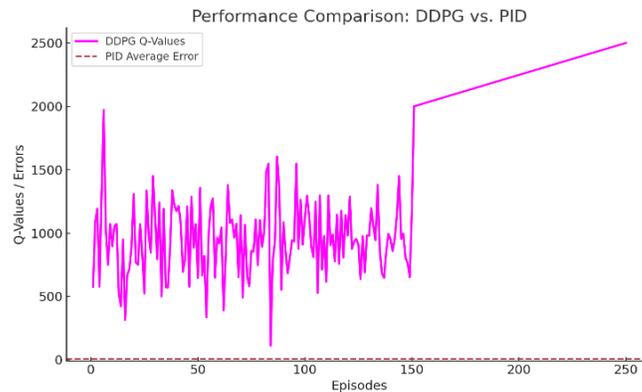


Figure 11: Performance Comparison between DDPG and PID

Integration Points in a Ship

The DDPG-based control strategy is typically implemented as a critical component of the propulsion control system. Several integration points within a ship's operational framework are identified where this strategy can be applied effectively.

1. Propulsion Control Unit (PCU):

The PCU is central to managing the propulsion system, including thrust generation and fuel efficiency. Integrating the DDPG strategy within the PCU software enables real-time monitoring

of thrust and fuel levels, allowing dynamic adjustment of propeller speed or engine power to optimize overall performance [1], [2].

2. Engine Control System:

The engine control system governs the main engine's operation, including fuel injection, speed, and efficiency. By interfacing the DDPG controller with this system, engine power output can be adjusted to achieve optimal thrust while minimizing fuel consumption [3].

3. Propeller Pitch Control:

The propeller pitch control regulates the angle of propeller blades to balance thrust and efficiency. The DDPG controller dynamically adjusts the propeller pitch based on environmental conditions, such as sea state and wind, as well as operational demands [4].

4. Dynamic Positioning (DP) System:

For ships equipped with a DP system, the DDPG controller plays a vital role in maintaining the ship's position and heading automatically. By managing thrust allocation, the controller ensures station-keeping while optimizing fuel efficiency, which is particularly beneficial in offshore operations [5], [6].

5. Power Management System:

The power management system is responsible for balancing power distribution between propulsion and auxiliary systems. Integrating the DDPG strategy into this system optimizes power usage by coordinating propulsion power with available electrical resources [7].

Benefits of Using DDPG in Ships

Implementing DDPG-based control strategies offers several advantages:

- **Improved Fuel Efficiency:** The DDPG framework dynamically optimizes propulsion to minimize fuel consumption, leveraging real-time operational data [8], [9].
- **Thrust Stability:** The strategy ensures consistent thrust even under varying environmental conditions, enhancing operational reliability [10].
- **Adaptability:** The system learns and adjusts to changing sea states, operational modes, and load conditions, making it highly flexible for diverse scenarios [11].
- **Reduced Emissions:** By lowering fuel consumption, the DDPG-based strategy directly contributes to reducing greenhouse gas emissions, meeting stringent environmental regulations [12], [13]. These benefits collectively lead to cost savings, as improved efficiency reduces operational expenses over time [14].

Conclusion

The DDPG-based control approach has restrictions even if it offers benefits. Although thorough, simulations are mostly responsible for the outcomes since they might not completely reflect the complexity of reality. Validating this paradigm with physical propulsion systems [15], [16] should

be the main emphasis of next studies. In addition, customizing the framework to fit various vessels and propulsion systems could call for huge customizing, a restriction observed in related research on AI-based vessel systems [17]. A different field of research is designing a successful reward function because future advancements require fine-tuning reward values to give particular operational goals, such as emissions reduction top priority [18], [19]. These constraints draw attention to areas where more research is needed to completely realize the possibilities of DDPG-based control techniques in marine uses. To improve generalizability and practicality, next directions consist in multi-objective optimization, real-time data integration, and validation on several vessel configurations [20]. The model assumes, reasonably, appropriate starting calibration of propulsion system parameters and sufficient computational capacity for real-time application. Among the restrictions are real-time operational requirements including adherence to safety and regulatory standards as well as limited data availability for some vessel types. Leveraging DRL's characteristics, the proposed design offers a flexible and efficient approach to maximize maritime propulsion systems, therefore tackling significant problems and providing a foundation for upcoming innovations.

This work addresses the long-standing trade-off between thrust generation and fuel economy by introducing a new application of the Deep Deterministic Policy Gradient (DDPG) algorithm to maximize marine propulsion systems. The proposed framework shows notable increases in propulsion efficiency, dynamic environmental condition adaptability, and fuel economy by using reinforcement learning. These results highlight how transformatively reinforcement learning can be used to solve challenging optimization issues in maritime operations.

The study adds especially to the field by combining cutting-edge reinforcement learning methods with a specially built simulation environment fit for marine propulsion systems. This method not only shows the efficiency of actor-critic designs for continuous control issues but also offers a scalable solution fit for several maritime environments. The findings provide operators trying to improve efficiency with useful insights while following more stringent environmental rules.

Although the study has its merits, it does admit to having some limitations. Accurate initial calibration and lack of real-world testing indicate improvement areas. However, these constraints enable future research. Integrating real-time operational data, adding multi-objective optimization, and validating the model in maritime scenarios are promising further research.

This research lays the groundwork for using AI to solve maritime operations problems. The success of reinforcement learning in optimizing propulsion systems signals a paradigm shift in energy management, environmental compliance, and autonomous maritime technologies. This study advances sustainable and intelligent maritime transportation by bridging simulation and application.

Acknowledgement

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Aden Container Terminal's Future: Opportunities, Threats, and the Role of Private Sector Participation

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المستخلص

تبحث هذه الدراسة في دور الشراكات بين القطاعين العام والخاص (PPPs) وأثرها في تحسين الكفاءة التشغيلية ودعم الميزة التنافسية للموانئ البحرية، وبشكل خاص محطة عدن للحاويات اليمنية. تسلط الدراسة الضوء على العقبات والآفاق التي يواجهها ميناء عدن، الذي يعاني من ضعف الكفاءة التشغيلية في مرافق والبنى التحتية للخدمات العامة الناجمة عن عوامل متعددة مثل تعدد الإدارات وعدم كفاية الخبرة التقنية. تؤكد الدراسة على الأهمية الاستراتيجية للشراكات بين القطاعين العام والخاص في جذب الاستثمارات الخاصة، وتسهيل نقل التكنولوجيا الجديدة، وتعزيز الكفاءة من خلال الممارسات الإدارية المعاصرة. حللت الدراسة حالات محددة من خلال إطار تحليلي وصفي من خلال استخدام مصفوفة التحليل الرباعي SWOT، مع تحديد العوامل الداخلية والخارجية التي تؤثر على جدوى الشراكات بين القطاعين العام والخاص في محطة عدن للحاويات، بما في ذلك المزايا الجغرافية والبيئية السياسية المعقدة. خلصت الورقة إلى أهمية وجود شراكة مناسبة مع القطاع الخاص المتخصص، ولكنها أيضًا اقترحت إجراء مزيد من البحوث حول الآثار الاقتصادية لمشاركة القطاع الخاص ومراجعة الأطر القانونية لتحسين دمج الشراكات بين القطاعين العام والخاص في إدارة الموانئ والعمليات، بهدف تعزيز مكانة عدن كمركز تجاري إقليمي.

الكلمات الدالة: مشاركة القطاع الخاص، التنافسية، محطة حاويات عدن.

Abstract:

This study examines the function of Public-Private Partnerships (PPPs) in improving the operational efficiency and competitive advantage of maritime ports, particularly the Aden Container Terminal in Yemen. The study examines the obstacles and prospects encountered by the Port of Aden, marked by inefficiencies in public service facilities and infrastructure stemming from variables such as administrative plurality and insufficient technical expertise. It underscores the strategic significance of PPPs in attracting private investment, facilitating the transfer of new technology, and enhancing efficiency via contemporary management practices. The research examines particular case studies through a descriptive-analytical framework and SWOT analysis, identifying critical internal and external factors affecting the viability of PPPs at Aden Container Terminal, including geographical benefits and a complex political environment. The paper concluded the importance in having appropriate partnership with the specialized private sector, however, it has also suggested further research on the economic impacts of private sector

involvement and reviews of legal frameworks to better integrate PPPs into port management and operations, aiming to bolster Aden's position as a regional trade hub.

Key words: Private Sector Participation, Competitiveness, Aden Container Terminal.

1- Introduction:

The shipping industry became a highly competitive industry (Tijan, et al., 2021). The combination of fierce competition, high capital intensity, and complete dependability on the global economy and oil price resulted in three major trends within the container shipping industry; increasing demand for larger container ships, the establishment of container shipping alliances, and the emergence of slow steaming. Containership sizes have significantly increased in the last two decades (UNCTAD, 2018). It has come a long way in its development since the beginning of containerization in the mid-1950s, with the world's largest containership currently reaching a staggering 24,000 TEUs as an Evergreen containership. Therefore, ports should increase their competitive position by attracting larger ships.

Competition in the port sector has significantly increased in recent years due to the dynamic environment shaped by numerous and interconnected forces influencing port operations. To survive and succeed, it has become imperative for ports to keep pace with advancements and modernization in maritime transportation and port services. This necessity has led many countries to seek strategic partnerships with the private sector, which specializes in port management and operations. Such collaborations aim to leverage the private sector's capability to provide modern management and inject the necessary financial liquidity for investing in advanced maritime ports and introducing modern technologies.

Different types of partnerships have emerged with the private sector, which differ from one country to another according to the nature and requirements of the country. Perhaps the most widespread and extensive type is Landlord PPPs (Habsi, et al., 2022).

2- Literature Review:

2.1 The importance of private sector participation

Many countries especially developing ones are facing the problem of inefficiency in the performance the public services facilities and infrastructure due to the large loss of output and the lack of the optimal use of labor, and the presence of many other problems encountered by governments in their management of the public utilities, such as administrative pluralism, lack of technical expertise, low levels of wages and lack of independence and the lack of effective anti-corruption mechanisms, in addition to the negative effects of the environmental caused by public utilities, due to negligence and poor maintenance, operation, and management (Chen & Guo, 2020).

The reasons and motives for the partnership with the private sector are summarized in the following points (Rashed & Shah, 2021):

- Weak efficiency of the government administration and its public sector in managing the utility and the public facilities, which was reflected in the high cost of public services with the deterioration.

- The infrastructure facilities hold paramount importance as they are critical drivers of economic growth and global competitiveness. Given the substantial investments required for infrastructure development, coupled with the governments limited financial resources and administrative challenges, it is clear that enhancing and optimizing these essential facilities cannot be achieved without effective collaboration with the private sector.
- Reduction of the financial burden placed on the governments to meet the increasing demand for public utility services and products, by finding additional alternative sources for financing the projects through the private sector, which will contribute to reducing the public expenditure.
- Participation with the private sector participation in infrastructure projects is an important direction to attract private investments, either national or foreign.
- The transfer of advanced technology from abroad through foreign investors and transfer of the modern management methods and techniques, whether from the national or foreign private sector.
- Time and cost reduction required for the establishment of new facilities, and energies and transferring the risks and burdens of projects to the private sector, which is capable of bearing and managing these risks.
- Improve efficiency in operating projects and respond quickly to the consumers' needs considering the private sector flexibility in moving and the advantage of the opportunities, making decisions, and responding quickly to any sudden problems, all are factors missed in government administration.

2.2 Previous studies focused on the private sector partnership in seaports:

(Wanis, et al., 2021) has analyzed the effectiveness of the PPP contribution to Maghreb Ports in achieving the United Nations SDGs goals, and it could benefit from their strategic location. Although its seaports suffer from lack and or insufficient infrastructure and superstructure this is due to their ownership structure as most of them are public port models, the research aims to describe sustainability and its dimensions in the seaport sector.

(Nezzari, et al., 2021) have examined the partnership with the private sector in the infrastructure projects, with the case study of the Central Port in Algeria. The researchers stated that the infrastructure projects are supportive of sustainable development, and the partnership between the public and private sector is one of its tools, given the existence of a financing gap, to reach a diagnosis of its reality in Algeria. The research concluded that the lack of funding and the weakness of the private sector negatively affected that. The research warned of the need to accompany the private sector while providing continuous incentives to the foreign investor to make the partnership in the central port project succeed to support development.

The research concluded that despite the great efforts of the public sector, especially the national one, to establish infrastructure projects and provide funds and equipment for their completion, the reality of infrastructure projects did not reach the set goals, especially the stage of lack of financial resources, which greatly impeded the continuation of the completion of projects, and this is what necessitated the participation of the private sector to contribute in supporting the developmental efforts. The researcher explained that the Algerian central port is distinguished from the rest of the

ports as it is a unique project of its kind in all fields, whether in terms of providing job opportunities, estimated at 200,000 jobs, in addition to the port's ability to compete with the rest of the ports located in the Mediterranean. The researchers also explained that the Algerian partnership model with the Chinese is a successful model for financing and setting up this project. The researchers also recommended the need to continue improving the legislative and regulatory framework for partnership in the field of infrastructure, which simplifies procedures between the public and private sectors.

While (Al-Omari & Hamid, 2022) have addressed the impact of the partnership between the public and private sectors on the infrastructure in Iraq, concerning the experience of the General Company for Iraqi ports. Furthermore, the research concentrated on infrastructure financing through effective partnership methods between the public and private sectors in the field of infrastructure. Whereas, the study's goal was to develop a successful solution and partnership methods, for enhancing the infrastructure development from both economic and developmental perspectives. The research identified the port transport sector as a specific area with weak infrastructure due to low absorptive capacity. However, they have proposed new methods for rehabilitating and developing port infrastructures through partnership systems and methods focusing on the benefits of the Partnership between the public and private sectors on the development of port infrastructure, increase of the annual capacity, and improve the competitiveness with other ports. The research identified various challenges, including weak infrastructure services due to economic, political, and security instability, as well as insufficient oversight and the absence of a legislative and legal framework regulating relations between contracting parties. Despite the obstacles, the research highlighted that Iraqi ports have witnessed rapid development to meet the requirements of growth and global trade volume.

(Capt.Al-Safaani, 2022) This study of the participation of the private sector and its impact on the performance of seaports, a case study was the port of Hodeidah, which is considered one of the most important studies that shed light on the participation of the private sector in Yemeni seaports and its role in developing and enhancing the performance of Seaports, despite the lack of Arab studies that dealt with the participation of the private sector in seaports in particular, The study aimed to identify the participation of the private sector and its impact in developing the performance of Yemeni seaports. The study methodology depended on the descriptive analytical approach; however, a questionnaire was distributed as the main tool for collecting the data concerning this study. It consisted of (40) items and the tool was applied to (200) Employees from all administrative levels, including (130) Hodeidah Port employees and also (70) private sector investors participating in Hodeidah Port, and by adopting some statistical methods to analyze data through the Statistical Packages Program (SPSS). The study reached several results, most notably: that the private sector participation was at a high level for all dimensions, at a rate of (76.40%), and in the seaport performance, it was also at a high level for all dimensions, at a rate of (77.40%). The study concluded with several recommendations, most notably: modernizing legislation and laws in the field of investment in the maritime transport sector, the participation of the private sector in modernization, creating a single electronic window to facilitate procedures and providing

the required services to customers, and finally involving the private sector to establish investment projects.

(A. M. Youssef, 2023) has examined in his research paper the privatization in Egypt, the researcher has clarified the positive aspects and the negative aspects, as well as reviewed the privatization of the maritime sector in Egypt and what are the pros and cons that will be reflected in the Egyptian economy as a result of privatization in addition to the impact of the privatization on the efficiency and performance of the maritime sector. However, opposition to the idea of privatization concluded through the research that privatization will increase the capital of companies as well as increase the financial liquidity in the state's public treasury, and also reduce the financial burden on the state's general budget. The research has relied on the survey to find out the pros and cons of privatization in the maritime sector in Egypt and has reviewed the experiments of the Sokhna Port and East Suez Canal port. The researcher has concluded that privatization should not be a sale of assets, but a privatization of public administration and liberation from rigid rules and regulations and it has a positive impact on the maritime sector in Egypt.

(Alshabi, et al., 2023), have analyzed in his research paper the feasibility for the application of Public private partnership (PPPs) at the port of Aden. However, the researchers have highlighted that the port of Aden has faced several challenges, including the ongoing conflict in Yemen, inadequate infrastructure, and insufficient financial resources. These challenges have hindered the port's growth and development and as a result, the Port's potential has not been fully realized. The researchers have used SWOT analysis to determine strengths, weakness, threats, and opportunities for applying the PPPs in Ports around the world, whereas the research has concluded that it is worth noting that PPPs in ports also face challenges and risks, such as contractual and regulatory complexities, political and social opposition, and financial risks. Therefore, careful planning, management, and evaluation are critical to ensure the success of such partnerships.

2.3 Research Gap and Contribution:

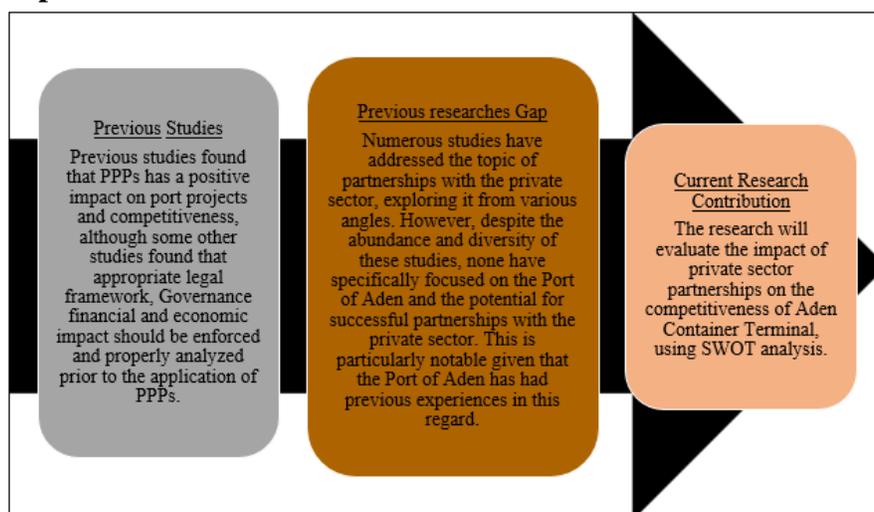


Figure (1) Research Gap and Contribution.

Source: By the Researcher 2024.

3- Research Problem:

Aden Container Terminal's groundbreaking public-private partnership, expected to revive the Port of Aden, which ended prematurely after four years. This study investigates the causes of this early dissolution, in compared with successful regional models and analysis the internal and external factors at the Port of Aden for the feasibility of new Public Private Partnership in future.

4- Research Aims:

This research aims to identify internal and external factors that influence the decision to pursue PPPs for Aden container terminal, however from the main research Aim, numerous of objectives are concluded as follows:

1. To analyze the existing obstacles and opportunities for the Port of Aden, focusing on inefficiencies in public service facilities and infrastructure.
2. To assess the impact of administrative plurality and lack of technical expertise on the operational effectiveness of the Port of Aden.
3. To explore the strategic importance of PPPs in attracting private investment and facilitating the transfer of new technologies.
4. To utilize a descriptive-analytical framework and SWOT analysis to identify key internal and external factors influencing the viability of PPPs at the terminal.

5- Research Methodology:

The methodology used is the descriptive-analytical approach, which involves collecting data and information related to the Port of Aden from various sources and analyzing them using the SWOT analysis tool (Strengths, Weaknesses, Opportunities, and Threats). This approach focuses on describing the current state of the port and interpreting the internal and external factors affecting its performance. The goal is to provide a comprehensive perspective that supports the development of strategic recommendations based on the analysis results.

6- Swot Analysis:

The researcher relied on the personal interviews with the key management in the port of Aden and his personal experience as a senior commercial manager for Aden container Terminal with a 25 years' work experience, in addition to the annual reports and the marketing strategic plan for Aden Container Terminal for the year 2024, which prepared by the Port of Aden and Aden container terminal commercial department.

Furthermore, some inputs from the electronically distributed survey were used to assess the effectiveness of the partnership with the private sector in the management, operation, and development of Aden Container Terminal. The SWOT analysis focused on analyzing the internal and external environment together, identifying shortcomings and weaknesses, and highlighting the strengths that distinguish Aden Container Terminal.

Through the analysis, it became clear that there are opportunities for the port of Aden if weaknesses are turned into strengths through finding appropriate solutions and treatments. Additionally, overcoming threats and developing plans that reduce the impact of threats on the

future of Aden Container Terminal requires government intervention. It is crucial to incorporate the development of seaports, specifically Aden port, into government programs and strategic plans for the post-war phase, which has exceeded eight years.

Therefore, the port management needs to develop a suitable strategy to ensure the continuity of the container terminal's activity and increase its market share, especially given the importance of the port's location as a significant advantage and a powerful position that cannot be overlooked and should be utilized.

SWOT analysis can be applied to assess the feasibility and potential success of implementing Public-Private Partnerships (PPPs) at Aden Container Terminal. This analysis is particularly aligned with the United Nations Sustainable Development Goals (SDGs), focusing on Goal 9 (Industry, Innovation, and Infrastructure) and Goal 17 (Partnerships for the Goals). The analysis aims to identify internal and external factors that may influence the decision to pursue PPPs for the terminal. By examining strengths, weaknesses, opportunities, and threats, this strategic evaluation will not only consider the operational and competitive aspects of PPPs but also their potential to foster sustainable development through improved infrastructure and effective partnerships (UNSDG, 2025), the SWOT analysis factors are as follows:

6.1 Internal Factors (Strength):

1. The geographical location enhances the importance of the port of Aden, especially its proximity to international shipping routes linking key global trade centers between the East and the West.
2. The port is a natural and year-round protected harbor, unaffected by wind seasons or climate disturbances.
3. It was one of the world's major maritime supply centers, which would restore its previous status if other factors were available.
4. It is characterized by a cheap and efficient workforce capable of working with competence and prowess.
5. It houses the largest and only container terminal in the Republic of Yemen equipped with high-efficiency facilities.
6. The container terminal is operated by advanced terminal operational systems (TOS).
7. The container terminal owns sufficient space to implement development projects, making the port of Aden a regional hub for transshipment trade.
8. The legislative and procedural structure in the container terminal qualifies it for partnership with the private sector, especially as it is built on a basis of collaboration with the private sector.
9. The container terminal at the port of Aden is an attraction for specialized private sector companies, given the mentioned points, as well as the Chinese government's interest in the Silk Road project, which cannot ignore the port of Aden.

10. The proximity of the port of Aden to international navigation routes helps reduce maritime shipping costs in the event of normalization of political and security life in the Republic of Yemen, contributing to the reduction of war risk fees.
11. The container terminal of the port of Aden is exempt from customs and tax restrictions as it is located within the geographical framework of the free zone, distinguishing it from the benefits of free zone laws.
12. The distance of the Aden container terminal from the city makes it an ideal location for managing business and service activities independently, which will enhance the private sector's desire to collaborate with the government sector to manage and operate the container terminal if other supporting factors are available.

6.2 Internal Factors (Weakness):

1. The security and political instability since 2011 have cast shadows on the service and commercial activities in the port of Aden, followed by the summer war in 2015 and its repercussions until today.
2. The closure of land routes from the port of Aden to local markets and population centers significantly affected the port's activities, doubling the costs of overland transportation for shipments entering the local market from the port of Aden to the northern and central regions of Yemen.
3. The imposition of a second customs duty in areas controlled by the Houthi group on shipments coming from the seaport in the port of Aden doubled the shipping costs through the port.
4. Levying duties and tolls on trucks carrying commercial shipments along the road extending from the port of Aden to population centers in the northern, central, and even eastern regions of the Republic of Yemen, where the eastern regions are under the control of the legitimate government.
5. Many industrial activities related to export and re-export have halted due to the war and political instability, further increasing the costs of container transport, especially since incoming containers generally return empty.
6. Administrative discipline has weakened as a result of the war's consequences and the lack of security and political stability.
7. Many workers have shifted to light work due to work injuries and aging, with no strategic plan for settling the old workforce and accommodating new workers based on competence.
8. Limited navigational depths and pier depth in light of the developments in container activity service worldwide and in the Red Sea region.
9. Equipment limitations, whether it's wharf equipment or yard storage equipment.
10. Limited storage areas and electricity connection points for refrigerated containers.
11. Despite being unique in the Republic of Yemen, the operational system of Aden Container Terminal is considered the oldest in the region when compared to leading container terminals in the Red Sea and the Gulf of Aden region.

12. Imposing war risk insurance fees has made the Aden Container Terminal a less preferable option for use by ships.

6.3 External Factors (Threats)

1. The continued security and political instability in the Republic of Yemen threaten to undermine commercial and service activities in the country, especially in the port of Aden.
2. The security instability in the Red Sea region and the increasing intensity of conflicts with the Houthi group, along with a lack of inclination towards peace, will multiply maritime transportation fees to Yemeni ports in general.
3. The existence of advanced and modern container terminals in neighboring countries' ports encourages many Yemeni importers to deal with them and then transport the shipments by land to Yemeni markets.
4. The ongoing closure of major land routes and the imposition of customs duties by the Houthi group on shipments coming from the port of Aden to its controlled areas double the shipping costs through the port of Aden.
5. The continued operation of the Hodeidah port without opening land routes from the port of Aden to local markets and population centers increases the cost disparity between the two ports for the sake of Hodeidah.
6. The deterioration of the local currency against the US dollar in areas under the control of the legitimate government mirrors the exchange rate situation in areas controlled by the Houthi group.
7. Non-payment of salaries and the worsening living conditions of Yemeni citizens due to the war and its repercussions, along with the absence of a political settlement among local conflicting parties, will further amplify the recession and reduce demand for goods and other necessities, affecting commercial activities in the city of Aden and its port.
8. The continued security and political instability will complicate forming partnerships with specialized private sectors to ensure the implementation of infrastructure and superstructure development projects in the port of Aden and the container terminal in particular.
9. Declining import activities through the port of Aden, with obstacles such as the opening of the Hodeidah port, road closures, increased maritime shipping fees, and the instability of the local currency, pose a significant threat to the activities of the port of Aden.
10. Equipment aging, wear and tear, an increase in light work cases among employees, and the laxity in addressing administrative discipline, coupled with rising operational expenses and declining income, threaten the activities and stability of the container terminal.
11. The absence of partnerships with the global and specialized private sector, which could work in collaboration towards the development and activation of the Aden Container Terminal's role, and enhance its competitiveness locally and regionally. Working on risk-sharing and addressing challenges collectively would prevent the continuous decline in the performance of the Aden Container Terminal and the widening of the technical and managerial gap between it and its counterparts in the region

6.4 External Factors (Opportunities)

1. The location of the port of Aden itself is considered an opportunity that must be exploited if the rest of the factors are available.
2. The announcement of peace in Yemen and power-sharing among conflicting authorities since 2011.
3. Neutralizing the port of Aden from conflicts and government interventions and granting it administrative independence.
4. Drawing up a strategic plan for the governance of Aden to support the city's service and commercial activities and enhance the city's vision for the next twenty-five years.
5. Declaring the city of Aden, a free zone with independent management will enhance its commercial activity and possess the Port activities for the imports and re-exports business.
6. Opening roads and creating dedicated routes for transporting shipments from the port of Aden to local market centers and enhancing the network of land road connections to reduce time and costs.
7. Activating the role of customs and supporting it to operate on a single-window basis in partnership with the port of Aden and other relevant entities.
8. Eliminating the multiplicity of security entities operating in the port of Aden, especially the container terminal, and integrating them into a specialized and highly trained unified entity.
9. Conducting studies that would work in partnerships with specialized private sector entities and ensuring the injection of funds to implement development projects in the port of Aden.
10. Collaborating with the government to enact legislation that would liberate the port of Aden from government restrictions and bureaucracy in dealing, especially the existing container terminal currently managed by a private company but subject to government procedures and restrictions that have constrained its ability to operate outside the scope of government procedures and bureaucracy. Also, liberating it from the existing laws in the Republic of Yemen through free market legislation.
11. Develop a Private partnership model towards the development of the Aden container terminal and execution of the expansion plans and enhance its competitiveness in the region.

The above analysis give identifies weaknesses that need to be addressed, as well as threats that could diminish the effectiveness of opportunities and weaken sources of strength. This situation obstructs the potential for development opportunities for Aden Container Terminal. However, these opportunities can be enhanced, and sources of strength supported, by fostering partnerships with specialized private sector entities, contingent upon achieving internal alignment among the various Yemeni political parties and their differing orientations. Such partnerships with the private sector will ensure sufficient capital is injected to complete stalled development projects and provide the necessary expertise to support strategic and marketing plans. This approach will enhance development projects and strengthen the competitiveness of Aden Container Terminal.

Therefore, from the researcher's perspective, the management of the Port of Aden should adopt the necessary strategies to support competitiveness. According to the researcher, two crucial strategies

need to be implemented: a defensive strategy and a remedial strategy simultaneously. The defensive strategy will leverage strengths against threats, while the remedial strategy will address weaknesses and capitalize on available opportunities to support and enhance the position of Aden Container Terminal both domestically and internationally.

7- Conclusion:

The Port of Aden holds significant potential for regional and international trade due to its strategic location. To fully realize these potential, investments in infrastructure, enhanced transportation networks, and modernized logistics systems are crucial. Ensuring administrative independence by neutralizing political interference and establishing autonomous management will streamline operations and boost efficiency. Creating a free trade zone with clear legislative frameworks, simplified customs procedures, and unified security operations will enhance the port's commercial appeal. Strengthening collaboration between the port authority and relevant entities will reduce bureaucratic hurdles and accelerate cargo handling processes, making the port more competitive. Moreover, fostering partnerships with the private sector through a well-defined public-private partnership (PPP) model can attract funding and expertise for expansion projects. Introducing supportive legislation to encourage investment and minimize government restrictions will further enhance the port's operational capabilities, positioning Aden as a leading trade hub in the region.

For further studies, the researcher suggests the following ideas for further studies related to the current research such as measuring the economic returns of private sector participation in Aden Container Terminal by conducting an economic impact analysis using input-output models to estimate the direct and indirect effects of private sector management. In addition to examining the legal and regulatory frameworks for private sector participation, including a legal review, comparisons with frameworks in competitive ports, and input from legal experts and stakeholders.

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Impact of Human Error on Maritime Industry: Case of Jamaica

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المستخلص

يشكل الخطأ البشري تحديًا كبيرًا في صناعة النقل البحري، مما يساهم في فقدان كثير من الأرواح، والخسائر الاقتصادية، والأضرار البيئية، وتقليص فرص العمل. تبحث هذه الدراسة في تأثير الخطأ البشري على صناعة النقل البحري على المستوى العالمي والإقليمي وفي جامايكا من خلال تحليل بيانات الحوادث لتحديد الأنماط المتكررة والعوامل المسببة. تتعمق الدراسة في العوامل الصحية، والنفسية، والبيئية، والتنظيمية، والتكنولوجية، التي تشكل أساس الخطأ البشري في المجال البحري. ثم يركز البحث على تقديم منظور تحليلي دقيق من خلال فحص بيانات الحوادث البحرية في جامايكا للفترة بين عامي 2009 و2023. تهدف الدراسة إلى تحديد التحديات المرتبطة بالخطأ البشري في جامايكا. تلجأ الدراسة إلى منهجية بحثية مختلطة؛ حيث يتم استخدام طريقة العينة البسيطة أولاً لتحليل ردود المشاركين وضمان مصداقية وحيادية الاستنتاجات التي تم التوصل إليها من البيانات فيما يتعلق بالبحث. من ناحية أخرى، يتم استخدام العينة الهادفة لتحليل الحوادث البحرية في جامايكا وضمان أن العينة تتناسب بشكل وثيق مع أهداف البحث، مما يزيد من دقة وموثوقية بيانات ونتائج الدراسة.

تهدف الدراسة أيضًا إلى تقديم توصيات فعالة للقضاء على الأسباب الرئيسية المسببة للأخطاء البشرية، وتحسين السلامة البحرية من خلال اكتساب المعرفة الكافية بتأثير الأخطاء البشرية على القطاع البحري على الصعيدين العالمي والمحلي لدولة جامايكا. في هذا الصدد، يقدم البحث توصيات ذات صلة لجعل البيئة البحرية أكثر أمانًا لجميع قطاعات صناعة النقل البحري على مستوى العالم وفي دولة جامايكا من خلال تحديد عوامل الخطر الرئيسية وتقديم توصيات فعالة. بشكل أكثر تحديدًا، يتضمن ذلك توصيات لاعتماد برامج تدريب متقدمة للطاقم، والتي يمكن أن تعالج الفجوات المعرفية الموجودة، وإنشاء طرق تواصل أكثر فعالية على متن السفن، وتعزيز وعي البحارة من خلال الحلول التكنولوجية ودعم استدامة/استقرار التوظيف والسمعة للعاملين في المجال البحري. بالإضافة إلى ذلك، تبرز التوصيات إرشادات لتحسين صنع واتخاذ القرارات من قبل الطاقم وتقليل تأثيرات الخطأ البشري. أخيرًا، يقترح البحث نهجًا شاملاً لمعالجة الخطأ البشري من عدة جهات نظر، مما يؤدي إلى انخفاض كبير في الحوادث البحرية على مستوى العالم، وفي جامايكا، والأهم من ذلك، في مصر.

ABSTRACT

Human error remains a significant challenge in the maritime industry, contributing to substantial loss of life, economic losses, environmental damage and employment reduction. This research investigates the prevalence of human error in maritime operations globally, regionally and in

Jamaica by analyzing accident data for identification of recurring patterns and causal factors. The study delves into the health, psychological, environmental, organizational and technological factors, underpinnings of human error within this complex domain. Then, the research focuses on the maritime industry to provide a localized perspective by examining the data of maritime incidents in Jamaica for the period between the years 2009 and 2023. The study aims to identify the unique challenges and vulnerabilities associated with human error in Jamaica. The research recourse to a mixed-method research methodology; the simple sampling method is first used to analyze participant replies and assure the legitimacy and impartiality of the conclusions reached from the data in relation to the research. Purposive sampling, on the other hand, is used to analyze marine accidents in Jamaica and guarantee that the sample closely fits with the research objectives, hence increasing the rigor and dependability of the study data and findings.

The research also aims to provide effective recommendations to eliminate major contributing causes of human error, and to improve maritime safety by gaining enough knowledge of the influence of human error on the marine sector both globally and in Jamaica. Finally, the research proposes a comprehensive approach for tackling human error from several viewpoints, thus leading to a significant decrease in marine accidents and incidents in Jamaica and worldwide.

Keywords- Human Error, Human factors, Maritime industry, Employment rate, Jamaica.

1- BACKGROUND

The maritime industry is an important facility. It has an obvious effect on the global economy because no other technologies can replace the shipping. It is the most economical means of transporting large quantities of cargoes between different ports around the world. It also includes port operations, oil and gas terminals operations, tug and barge operations, pilotage, chartering of ships, passenger and pleasure operations, vessel classifications, marine insurance, maritime communication with ports or ships, recreational boats and yachts and many other maritime operations and activities, either offshore or onshore. Shipping and shipbuilding have to cope with and fulfil the large developments in the maritime industry requirements for supporting the adoption of maritime conventions, marine insurances, maritime arbitration, and maritime education and training (Daniels, 2024). The demand of building new ships with modern advanced technology has increased in the shipbuilding industry. Therefore, the human element is the most important responsible factor for running all the maritime operations and activities, implementing the international and local maritime regulations, maritime safety, maritime security, modern ship technologies and any other related activities, and is the secret of failure or success for any maritime company (Vedat et al, 2018). Moreover, it is an important factor in improving the maritime safety, commitment from the management level of any maritime organization, effective control and monitoring, maritime training, efficient maritime education and safety culture concept's implementation. Most of the maritime operations look for high quality trained crewmembers to be harmonized in shore-based management and on board ships to enforce safety, environmental protection and competitive ship management. The human elements impact extends to the entire crew activities, shore based management team, shipyards and all personnel related to the maritime operations. The primary aim of the International Maritime Organization (IMO) is to

mitigate the human element impact to enhance the safety of life at sea for crew and passengers on board ships or in the offshore industry, maritime safety, maritime security and marine environmental protection, as dictated by its resolution (A.947 (23), 2003). Studies stated that 75-96% of the maritime accidents in different maritime operations fields occurred due to the human error (Canter, 2024). The human element is a cumulative complex problem, which affects the ships worldwide. It affects the safety of life of the crew on board cargo ships, safety of life of the passengers on board passenger ships and pleasure ships, maritime safety, maritime security, marine environmental protection and safety of maritime operations for different types of ships (Barnett and Pekcan, 2017). The human error types are operational human error and managerial human error based on the role of work of the staff member in any maritime operations. This research study presents the human error impact on maritime safety with application on Jamaica due to the availability and reliability of data and information. Results and methodologies of this research are applicable on Egypt once research data are available due to the important geographical location of Egypt and its enhancement in international supply chain in the maritime industry.

2- METHODOLOGY

The research design used and implemented mixes quantitative and qualitative research methods (Leedy & Ormrod, 2014), with the aim to provide the research with the strengths that can cover the weaknesses of the usage of either method alone. In addition, it provides a full comprehensive coverage and understanding of the research problem. It also aims to conduct a sample survey, using a survey questionnaire consisting of (9) questions to identify the actual causes of human error in the maritime industry in Jamaica.

In addition to the survey questionnaire, interviews carried out with representative of the Marine Investigations Department at the Maritime Authority of Jamaica (MAJ) for relevant data on types of marine incident have been arranged between the years 2009 to 2023. Furthermore, interviews have been conducted with the representatives of the Marine Pilotage at the Port Authority of Jamaica, port operation managers at Kingston port, Montego bay port, Discovery bay port and Falmouth port, marine superintendents of national maritime companies in Jamaica, crewing and manning recruitment representatives and yachts sector representatives.

Data for study of reported marine incidents and casualties for years 2009 - 2023 has been obtained from European Maritime Safety Agency (EMSA). In addition, data has been collected from the International Maritime Organization's data platform (Global Integrated Shipping Information System (GISIS – IMO) for the years between 2009 – 2023 for worldwide maritime incidents and casualties. As also (GISIS – IMO) gathered data assisted in the study of Caribbean region maritime incidents for the years between 2009 – 2023. Data had been collected from the Marine investigation department at the Maritime Authority of Jamaica as it shows the number and types of marine incidents in Jamaica between years 2009 to 2023.

Instruments: The instrument used for gathering the data was a combination of quantitative and qualitative data gathering instruments. The quantitative research instrument used for gathering the

data for the purpose of the research was the survey questionnaire and the qualitative research instrument used for gathering the data for the purpose of the research was the interviews.

Sampling: The sample size of the research consists of fifty-five persons due to their availability and capability at the time of this survey. Fifty persons who are engaged in maritime operations on ships, ports and maritime companies and five persons who are in responsibility of supervision of the maritime safety, marine pilotage, maritime training and education, port operations, yachts, recreation and pleasure activities and crewing and manning of seafarers. The sampling methods used in this research were the simple random sampling method, and purposive sampling method.

The simple random sampling method was selected to ensure that each participant in the questionnaire survey had equal opportunity of selection. The simple random sample of this research was chosen to ensure the credibility and impartiality of the conclusions drawn from the findings as they relate to the research (Leedy & Ormrod, 2005). The Simple Random Sampling Method used for (50) fifty persons who are engaged in maritime operations on ships, ports and maritime companies. According to (Leedy & Ormrod, 2005) this sampling method was selected for the interviewees based on particular knowledge, experience and their responsibilities in the maritime industry in Jamaica. The purposive sampling considered (5) five officials who are in charge of the maritime safety, marine pilotage and ports operations, maritime training and education, yachts and recreation activities, and crewing and manning of seafarers in Jamaica. Other officials were also targeted, but their stuffed time schedules and work engagements made it very difficult to meet with them at the time of research.

Method of analysis: Data were collected from the questionnaires and interviews are analysed using descriptive statistics. This descriptive static approach enabled the results to be presented in tables, graphs and other forms of diagrams, as suggested by (Cox, 2017). Analysis was conducted by the use of computer programme Microsoft office Excel 2010).

3- RESULTS AND DISCUSSION

Marine casualties and incidents worldwide: According to the reports of the European Maritime Safety Agency (EMSA, 2023) and Global Integrated Shipping Information System (GISIS – IMO, 2023), Figure (1) shows the number of reported marine casualties and marine incidents between year 2009 – 2022 with different levels of severity. The total number of reported marine casualties and incidents over this period was 30422. The total number of reported marine casualties and incidents in 2022 was 2,510. In relation to the severity in year 2022, 53.3% of the reported marine casualties and incidents were less serious, 24.4 % were serious, 1.7% were very serious and 20.6% were marine incidents (EMSA, 2023).

In addition, Figure (2) shows the number and type of marine incidents and casualties that happened worldwide over the same period. It illustrates that marine incidents caused by collision were 5915, loss of propulsion power 5089, contact with berths 3614, loss of equipment 3400, grounding/stranding due to power failure 2356, fire and explosion 1870 and loss of directional control 1745. In addition, grounding/stranding due to other operational causes like human error

were 1101, flooding 967, loss of containment 939, loss of control power 123, capsizing due to listing 991, hull failure 690 and other operational causes contributing to marine incidents causation 185.

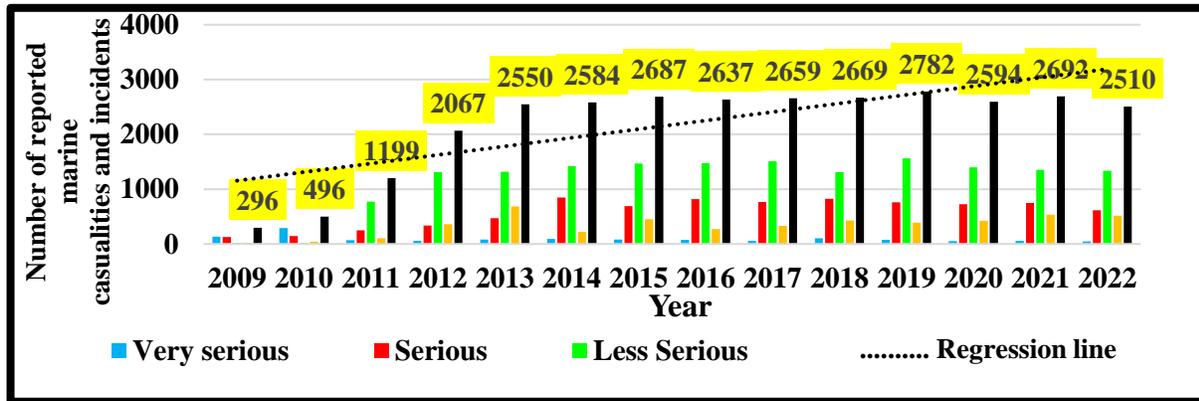


Figure (1): Number of marine casualties and incidents worldwide (2009 – 2022)
Source: EMSA and GISIS-IMO (2023)

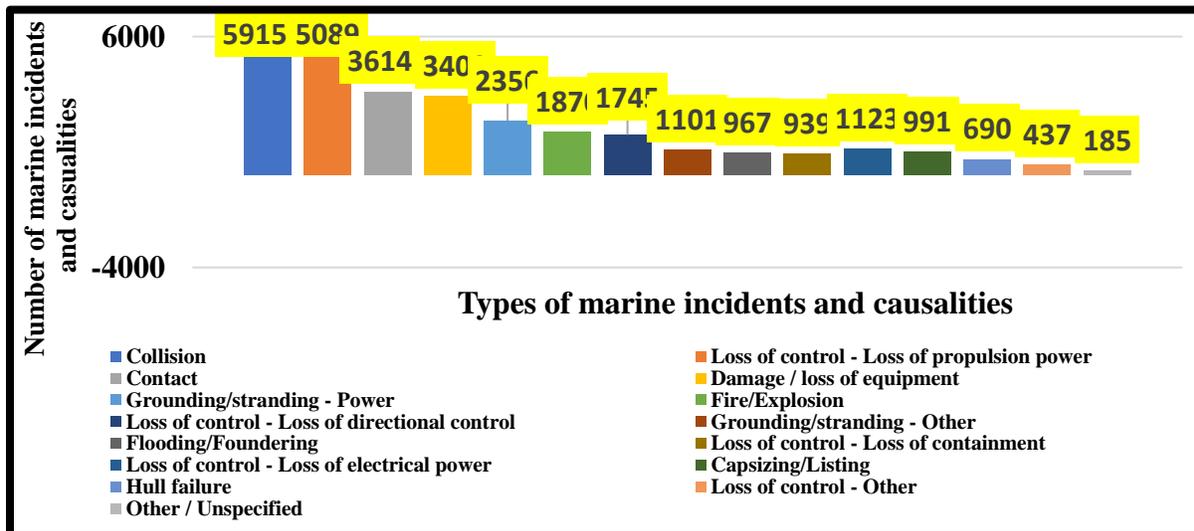


Figure (2): Number and type of marine incidents and casualties worldwide 2009 - 2022
Source: EMSA and GISIS-IMO (2023)

Contribution of Human factor to maritime casualties and incidents: Human actions and associated elements influence accident occurrences. Figure (3) shows the percentage of contributing elements affected by humans, as determined by taking into account all relevant aspects. Between 2014 and 2022, the human element had an average effect of 80.7% on the contributing elements. Fishing vessels have the lowest human effect (76.1%), whereas other ships have the most (87.7%). Cargo, passenger, and service ships have an effect equal to or higher than 80.1% (EMSA, 2023).

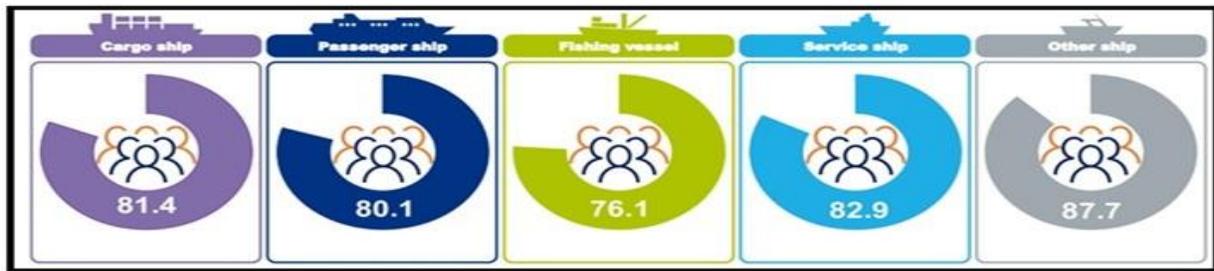


Figure (3): Percentage of human element contribution in marine casualties and incidents
 Source: EMSA (2023)

Marine casualties and incidents in Caribbean region: Figure (4) shows that (107) marine incidents affected the Caribbean region including Jamaica between the years 2009 – 2023 with different types and impact. It indicated that marine casualties and incidents increased in years 2012 and 2016 with fifteen and thirteen incidents, respectively, due to improper implementation of safety procedures on board and lack of organizational supervision.

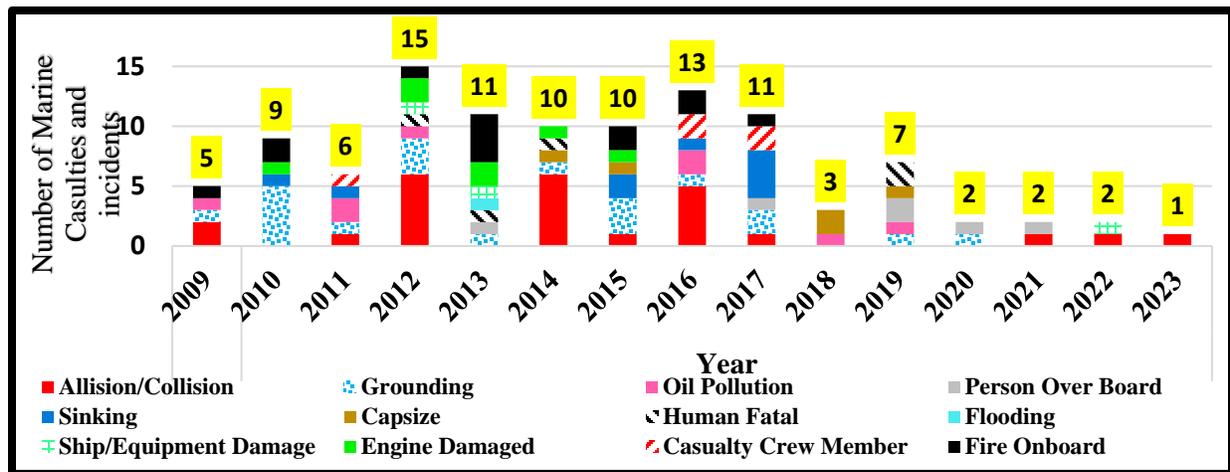


Figure (4): Number of marine incidents in the Caribbean Region
 Source: GISIS - IMO (2023)

Some (107) marine incidents affected the Caribbean region including Jamaica as follows: (25) allision/collision, (20) grounding, (8) oil pollution, (5) casualty of crew members on board ships, (13) fire, (6) person overboard, (9) sinking of ships, (5) ships capsize, (5) human fatal, (7) engine damage, (3) ship/equipment damage and (1) flooding. Data analysis showed a sensitive and tangible contribution of Jamaican marine incidents to the Caribbean region marine incidents.

Marine casualties and incidents in Jamaica: Figure (5) shows that between 2009 – 2023 a total of forty marine incidents and casualties happened with various types between allision/collision at the years 2012, 2014 and 2016. The grounding incidents have increased in 2010; oil pollution has increased in 2011 and 2016, incident affected crewmembers increased in 2016 and 2017 and fire on board incidents increased the years 2015 and 2016. Figure (6) illustrates that 37.5% of marine incidents were allision/collision, 25% grounding, 20% oil pollution, 12.5% affected crewmembers and 5% fire on board ships.

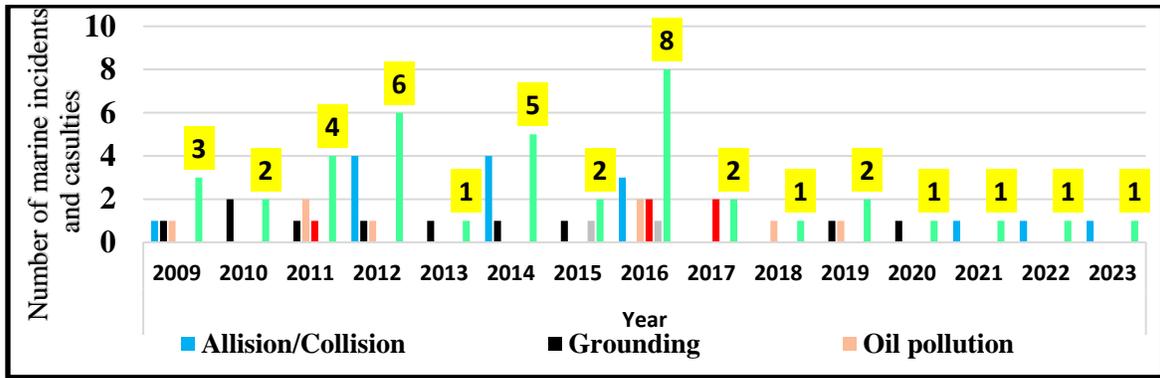


Figure (5): Number of marine incidents and casualties in Jamaica 2009 – 2023

Source: Maritime Authority of Jamaica (2023)

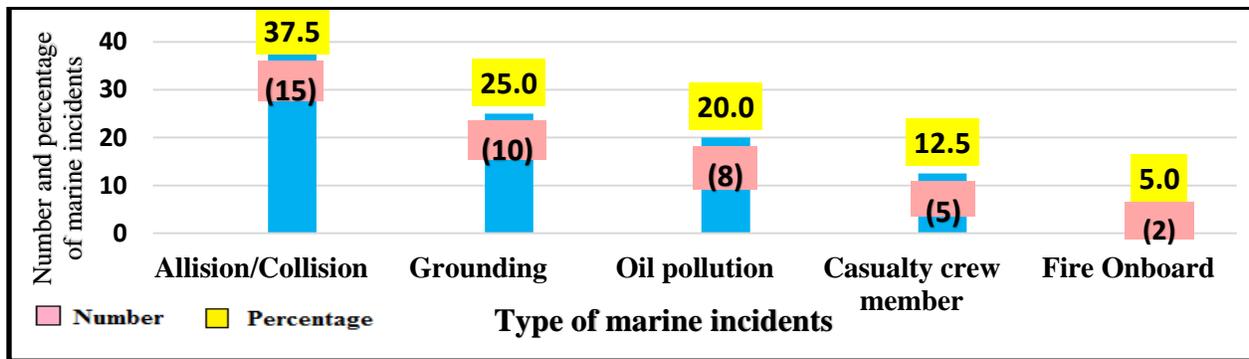


Figure (6): Frequency of marine incidents in Jamaica 2009 – 2023

Source: Maritime Authority of Jamaica (2023)

Contribution of Marine Incidents in Jamaica to those in Caribbean Region: Figure (7) illustrates the numbers of marine incidents in Jamaica as effective factor in Caribbean region marine incidents.

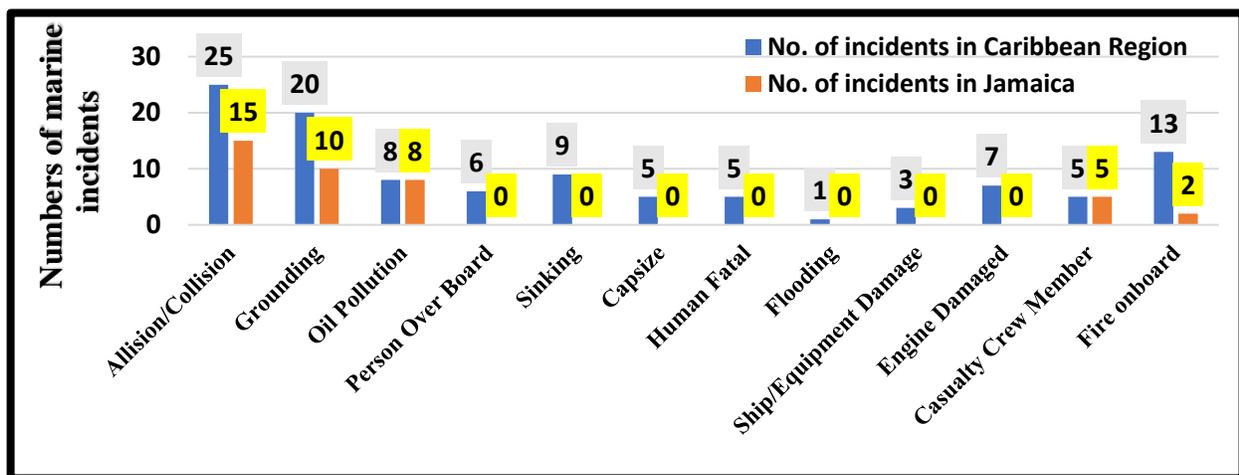


Figure (7): Number of marine incidents in Jamaica and in Caribbean region

Source: GISIS - IMO (2023)

Note that the (15) allision/collision marine incidents in Jamaica represent (60%) of the total number of this type of incidents in the Caribbean. Similarly, grounding marine incidents (10 in Jamaica) represent (50%). On the other hand, Figure (7) indicates that (100%) of oil pollution marine incidents (8 incidents) and casualty of crew members on board ships (5 incidents) occurred in Jamaican waters. Also, (2) fire incidents in Jamaican waters, out of a total of (13) fire incidents in the Caribbean region, represent (15%).

Questionnaire findings: Research questionnaire surveyed different occupational sectors, which give the results for reliability and validity to answer the research questions. Participation to questionnaire survey conducted by experienced persons, which give more accuracy to the research results. Local maritime sector experience made the survey reached deeper to explore the actual causes of marine incidents in Jamaica. Different maritime work sectors helped the researcher in investigation and exploration of marine incidents causation and contributing factors led to those incidents. The survey showed that lack of training and maritime education mostly the main factor in causation of marine incidents. In the same time, lack of maritime education and training could be considered the opening gate for occurrences of the other factors such as organizational and managerial factors, unsafe supervision, environmental factors, ship’s design factor and lack of communication which indicated by participants.

Survey shown in figure (8) that human error has a clear participation in marine incidents causation by 51% - 75% according to questionnaire survey. Participants indicated that marine incidents caused damage to the ships, ports constructions and equipment, marine pollution affected Jamaican ports. In addition, it caused casualties and loss of life to related staff. In addition, it has an economic impact on the local and regional maritime industry and a clear impact of the reputation, employment rate and competitiveness of seafarers.

Human error causation is mostly due to lack of training and maritime education, workload and fatigue factors, skills factors, organizational factors and commercial pressure. Figure (9) shows a clear indication of statements that human error reduced the employment rate of seafarers and shore personnel jobs. Also, it affects the seafarer’s future and on shore operators employment sustainability.

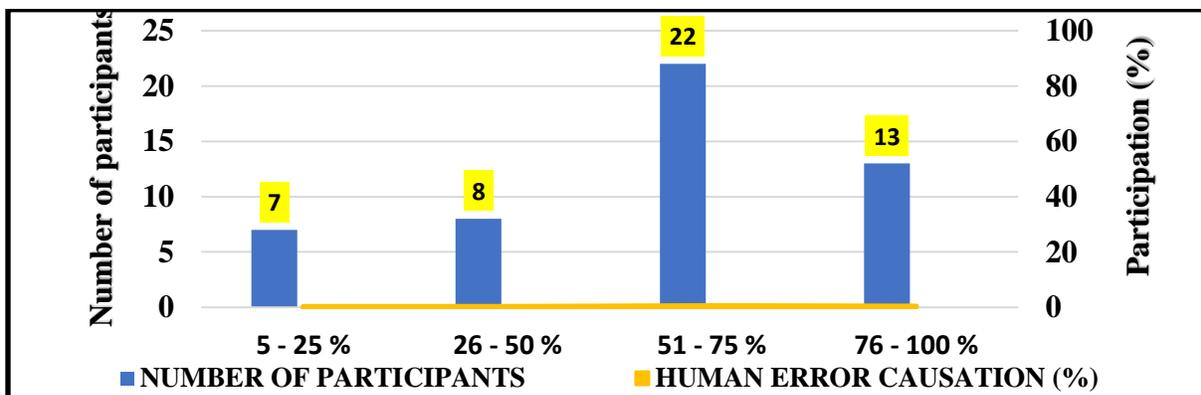


Figure (8): Causation of maritime accidents in Jamaica

Source: Author (2024)

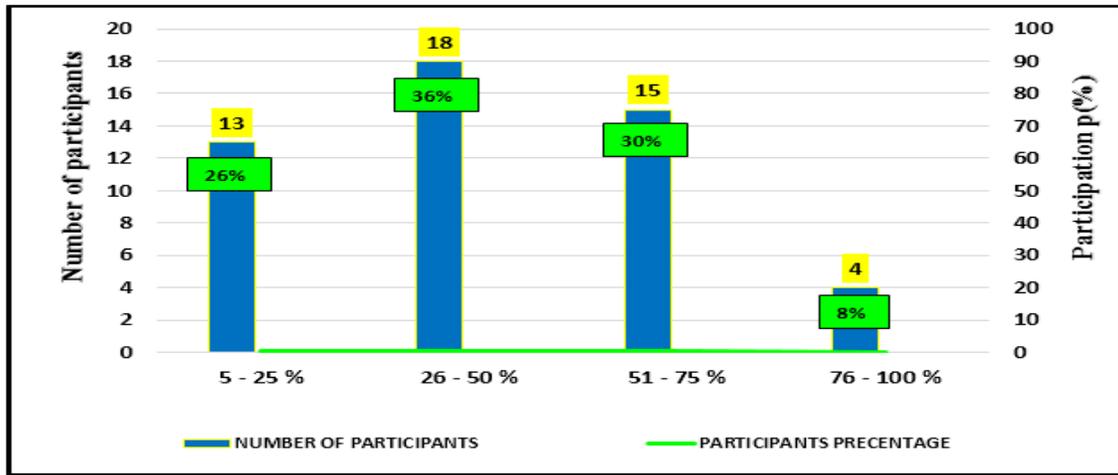


Figure (9): Effect of human error in employment rate reduction in Jamaica percentage
 Source: Author (2024)

Interview findings: Figure (10) shows that two interviewees attribute causation of marine incidents in Jamaica primarily to lack of seafarers maritime education and training. While lack of organizational procedures, managerial supervision, environment and weather condition effects, inadequacy of ship design, and communications and language barriers were individually judged as the primary cause by one interviewee only. Furthermore, four interviewees are of the opinion that human error is the primary factor in marine incidents in Jamaica.

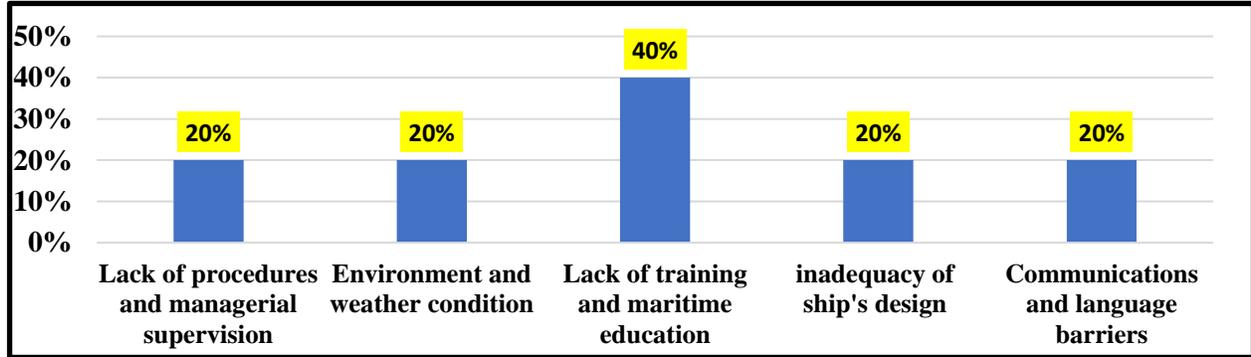


Figure (10): Causation of Marine incidents in Jamaica
 Source: Author (2024)

Referring to Figure (11), one interviewee sees that workload, stress and fatigue are the main causes of human error. In addition, two interviewees think that lack of teamwork, knowledge, training, knowledge, experience and communication barrier are the most influential contributing factors. While one interviewee states that lack of organizational policies, crew resource management, and supervision are the main causes of human error initiation; he also sees that the commercial pressure induced by focusing on profitability is one of the vital causes of human error.

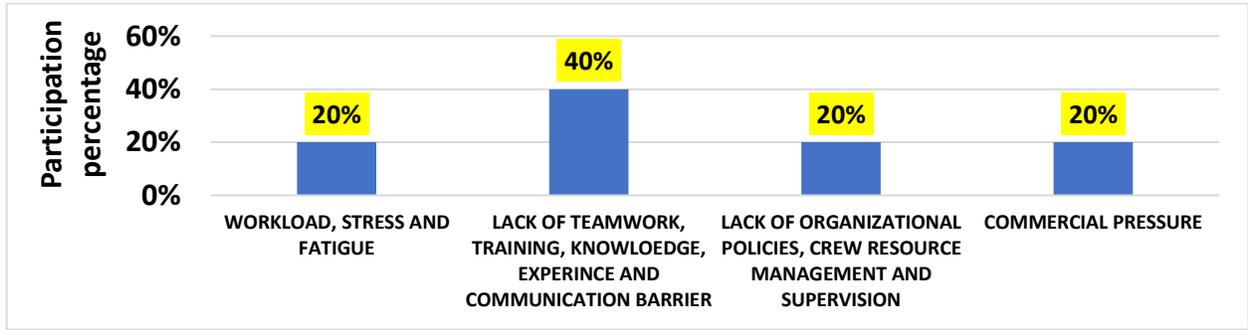


Figure (11): Percentage participation of human error sources in the marine incidents in Jamaica

Source: Author (2024)

Figure (12) shows that two interviewees addressed the negative impact of human error on seafarers’ life, three pointed to the negative impact on damage to ships, ports construction and equipment, three mentioned the economical, three confirm the negative impact on reputation and competitiveness, and two maximize the effect on marine pollution.

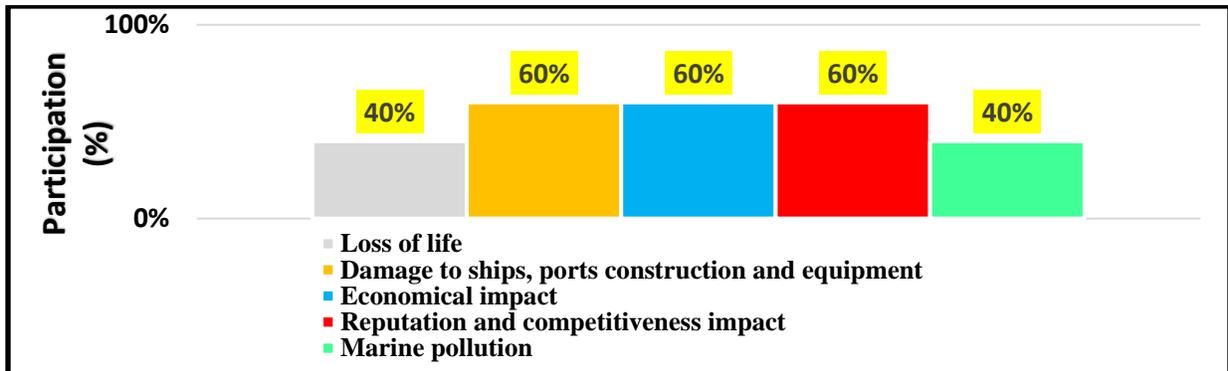


Figure (12): Human error impact on maritime industry in Jamaica

Source: Author (2024)

Moreover, the interviewees’ opinion differed when it came to the effect of human error on employment rate. Whereas three interviewees assigned a weight of (51-75%) to that effect, one interviewee only assigned a weight of (5-25%) and another assigned (26-50%), as shown in Figure (13).

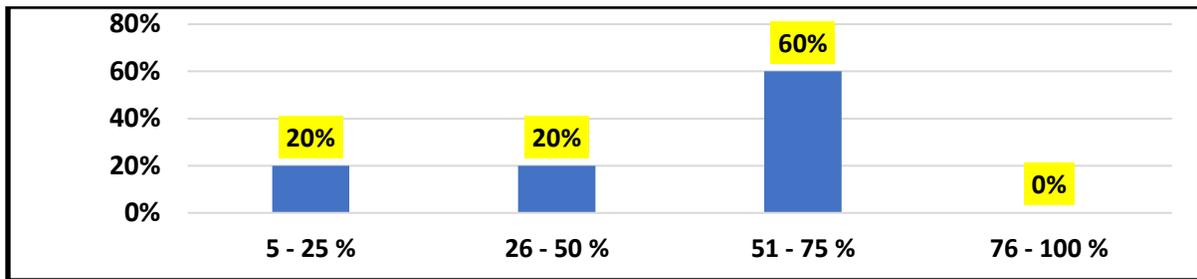


Figure (13): Effect of human error in employment rate reduction in Jamaica percentage

Source: Author (2024)

Three of the interviewees indicated that some procedural measures have been taken in some of the maritime shipping companies to reduce the inlet of some contributing factors of human error such as checklists, work permits, monitoring and supervision systems but effective implementation of those procedures is yet to be enforced. Also, shortage of financial resources in some of maritime companies and the limited view of those companies toward the profitability of such procedures retard their activation. In addition, two of the interviewees see that the overlooking and delaying of maritime companies' managers to decide in investment of their workers or crew through maritime training and education made the efforts of human error reduction techniques unfruitful.

4- CONCLUSION

The study highlights the importance of human error in marine incidents and the need for a comprehensive approach to safety management. The Jamaican marine industry shares vulnerabilities with other international sectors, such as poor training and resource restrictions. To reduce these risks and promote a sustainable marine economy, a diversified strategy is required, including better training, strengthened safety rules, and enforcement. The study found that human error in maritime incidents in Jamaica is a fact, primarily due to a lack of training and maritime education. Other factors such as organizational and managerial factors, unsafe supervision, environmental factors, ship design factors, and lack of communication also contribute to these incidents.

The limited awareness of human error causation and impact in marine incidents in Jamaica suggests the need for more effective measures to mitigate this issue. Recommendations include training maritime companies' managers on professional leadership, supervision, and motivation, as well as addressing the commercial pressures of some managers. Strategic investments in technology and a strong safety culture that prioritizes error reporting can help minimize accident risks while protecting the marine environment and the livelihoods of seamen and port operators. By promoting a culture of safety and reporting, the marine sector can make significant gains in minimizing human error effects while maintaining the environment and seafarers' lives.

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Evaluating the Impact of AI Tools on the Performance of Maritime Trainees in METI

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المستخلص

تتغير صناعة النقل البحري كثيرًا بسبب التكنولوجيا الجديدة، واستخدام المزيد من الآلات، والأدوات الرقمية. ومن أجل الاستمرارية في التنافس، يجب على المؤسسات التعليمية البحرية تنفيذ تقنيات التدريس المحدثة التي تمكن الطلاب من اكتساب المهارات اللازمة لفرص العمل القادمة في هذا المجال. تستكشف هذه الدراسة كيف يمكن للذكاء الاصطناعي وتحليل البيانات أن يجعلوا قياس المهارات في برامج التعليم والتدريب البحري أفضل وأدق.

يساعد الذكاء الاصطناعي وتحليل البيانات في جعل التعلم أكثر ملاءمة وفاعلية للأفراد، ويسمح بالتتبع السريع للتقدم والتطوير، ويمكنه توقع النتائج المستقبلية، حيث يوفر مساحة آمنة للمتدربين لاكتساب الخبرات بشكل أوسع. كما إنها ستساعد في الحكم على مدى جودة المتدربين في اتخاذ القرارات وحل المشكلات وأيضاً استخدام قدراتهم الفنية المكتسبة. ومن خلال استخدام أدوات الذكاء الاصطناعي وتحليل البيانات، يمكن للمعلمين ومدربين معرفة الأجزاء التي يحتاج فيها الطلاب والمتدربين إلى المساعدة وتركيز، ووضع خطط تدريب مخصصة لكل طالب، وتخمين مدى نجاحهم في المستقبل.

استخدمت هذه الدراسة طرق بحث مختلفة. حيث تم النظر في الدراسات الجديدة، والتحقق من الأمثلة المتاحة، كما تم تجميع المعلومات من المؤسسات التي تتولى التعليم والتدريب وتطوير المهارات البحرية. حيث توضح الدراسة كيف تجعل اختبارات الذكاء الاصطناعي مهارات الفحص والتقييم أكثر موثوقية ودقة وسرعة. وتُظهر النتائج أن استخدام الذكاء الاصطناعي وتحليل البيانات يحسن دقة التقييمات ويساعد في تغيير العملية التدريسية والتدريبية بما يلبي الاحتياجات الملائمة للتغيير المستمر في صناعة النقل البحري. وتساهم هذه الدراسة في تطوير استراتيجيات تعليمية جديدة تهدف إلى تجهيز عاملي القطاع البحري لمواجهة التحديات التي تفرضها التقنيات الناشئة والمتطورة.

Abstract

The Maritime industry is changing a lot because of new technology, more machines doing work, and the use of digital tools. To stay important and useful, maritime schools need to use updated teaching methods that give students the important skills they need for jobs in the future. This study looks at how artificial intelligence (AI) and data analysis can improve the way skills are measured in maritime training programs, making the assessment more accurate, efficient, and complete.

AI and data analysis help make learning more tailored to individuals, allow for fast tracking of progress, and can foresee future outcomes. This helps us see what the trainees know and can do more clearly. These technologies are capable of replicating actual ocean environments, providing a safe space for trainees to gain experience. They help judge how good trainees are at making choices, solving problems, and using their technical abilities. By using AI tools and analyzing data, teachers can find out where students need help, make custom training plans for each student, and guess how well they will do in the future.

The study uses different methods. It looks at new studies, checks out examples, and gathers information from schools that teach maritime skills. It shows how AI tests make checking skills more reliable, accurate, and quicker. The results show that using AI and data analysis improves the accuracy of assessments and helps training change to meet the changing needs of the shipping industry. This study contributes to the development of a fresh educational strategy aimed at equipping maritime employees to face the challenges posed by emerging technologies and automation.

Keywords: maritime education, competency-based assessment, AI, data analytics

Introduction

Training and education in the maritime field are key for a strong and lasting shipping industry. It supports the education of people to acquire expertise in professional roles within business and other areas. As global trade and shipping become more complicated, there is an increasing demand for new ideas in Marine Engineering Technology (Sharma & Nazir, 2021). It's important for businesses to have skilled and adaptable workers so they can remain strong and meet the changing needs of global trade. The adoption of modern technologies in Maritime Education and Training regulations and initiatives has become increasingly vital in recent times. Digital software, Artificial Intelligence (AI), Machine Learning (ML), and data analysis provide significant opportunities to improve training and skill assessment. The COVID-19 pandemic showed us how important it is to be able to adapt and deal with unexpected problems. This led to a quick change in how we teach and use technology in maritime education, especially for training officers.

Even with these changes, there are still big problems. The shipping industry faces many problems, like new worldwide rules, changes in technology, and challenges in managing different types of workers. Everyone thinks that MET is really important for fixing these problems. But we haven't fully explored using new tools like AI and data analysis in MET (**Jensen & Konradsen, 2018**).

This study examines how using AI and data analysis can make skill-based tests better in maritime education. It wants to solve important problems, like keeping users interested, making learning fun, and helping students use what they have learned. This study explores how various technologies can make teaching and learning better in maritime studies. The goal is to give useful ideas that help students connect what they learn with the jobs they will have in the maritime industry. This will prepare people for maritime jobs to face the challenges of a more digital world.

Hypothesis

This study examines the integration of AI and data analysis Techniques in the training and evaluation processes of Maritime Education and Training

(H1): AI and data analysis improve MET skills tests, making them more accurate and effective than old ways.

(H2): Using AI to evaluate skills keeps students engaged and excited by giving them personalized feedback and tailored learning plans.

(H3): The application of data analysis within MET aids in anticipating trainees' success while also highlighting aspects that need further development. This helps make training programs better.

(H4): Using AI tools like augmented reality and machine learning makes training for maritime skills better and more interesting by providing hands-on experience. These ideas look at how new technologies can enhance maritime training, making sure it meets the changing needs of the global shipping industry.

Methodology

This study looks at what MET trainees and students think and feel about AI technologies in MET. The study uses a method that focuses on understanding people's experiences better. The study uses qualitative research methods for several reasons. For instance, it can be adapted to suit various contexts and aids in grasping individuals' perspectives, emotions, and knowledge regarding the subject under examination. **(Creswell & Poth, 2018).**

Qualitative research can provide answers to questions that other surveys usually overlook. The Research looks at reality as made up of different parts and levels. This means that people in the research might see the topic of new technologies and MET in different ways.

The interpretive approach is based on specific ideas about knowledge **(Creswell & Poth, 2018)**. In order to comprehend the impact of new technology in MET on emotions and experiences, it is essential to gather insights from both educators and learners involved in the program. Interpretive research uses natural methods, like having conversations with people, to help the researcher understand and find deeper meanings in their studies. This method means having conversations with people to understand their thoughts and feelings better. This helps collect important details about how new technologies relate to MET.

The study examined social constructivism. This means that everyone thinks differently and sees things in their own way. The goal of the study was to find a shared idea in these different explanations. Researchers utilize qualitative, semi-structured interviews to explore and comprehend how people perceive and experience a particular topic **(Lauterbach, 2018)**. These interviews are a key way to gather information in research about people's experiences and opinions. The proposed strategy involves conducting semi-structured interviews to collect in-depth insights on the connection between new technologies and MET.

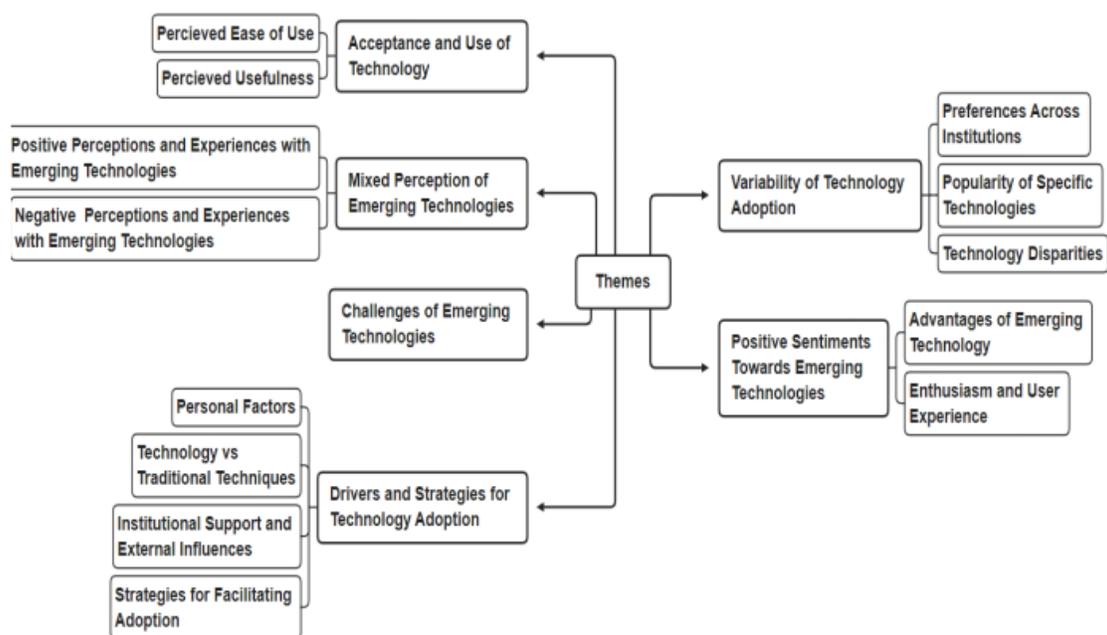


Figure 1: Themes and Subthemes from Interview Data Analysis

Phenomenological Approach

Phenomenology is a method of learning about how people really feel and what they go through in their lives. This technique provides us with a clearer picture of the feelings and opinions of MET teachers and students about employing AI tools. The aim is to understand the key ideas of their experiences, according to Moustakas (1994) and Creswell & Poth (2018). This strategy centers on people's engagement with technology and their diverse emotional responses to it. Factors like what users think about how easy technology is to use, how helpful it is, and their opinions on it are very important.

Data Collection Methods

The main way we collected data was through detailed interviews. These interviews aimed to understand the real experiences and feelings of the participants. The interviews were done on Zoom and were set up in three parts, each lasting 60 to 90 minutes. They included questions about personal information and the situation. Asking more questions helped gather better information, which was noted down (with permission) for writing out and later studying.

Data Analysis Procedures

The interview recordings were studied using a method called thematic analysis, with the help of a software called Nvivo 14. Codes were created, sorted into groups, and improved into main ideas. This repeating process involved combining notes, memos, and comments from researchers. The themes were made clear with direct quotes from the participants, helping to understand their stories better.

Literature Review

The worldwide shipping industry is exceedingly complex and faces various interconnected challenges, counting stricter directions, quick mechanical progressions both inside and exterior the industry, and issues related to a progressively assorted workforce. These challenges highlight the significance of creating an exceedingly gifted sea workforce to guarantee the industry's long-term maintainability and victory (Boguslawski et al., 2022). Concurring to Erdogan & Demirel (2017), Sea Instruction and Preparing (MET) plays a basic part in forming the quality of execution inside the shipping segment. Their think about found that current worldwide endeavors to improve MET center on completely supporting preparing programs, reinforcing collaboration between MET educate and the industry, surpassing the least ability necessities for seafarers, and expanding the number of well-trained and certified sea experts. In this setting, Jensen & Konradsen (2018) pointed out that in spite of critical endeavors to move forward MET quality, essential challenges endure and require inventive arrangements. With the expanding dependence on advanced innovation in preparing, it has gotten to be basic to coordinated innovative devices into MET programs to improve preparing productivity and in general oceanic execution. Additionally, Sharma & Nazir (2021) highlighted that the oceanic industry forces rigid competency prerequisites, making the appropriation of rising advances a need to bolster preparing forms and guarantee compliance with universal guidelines. Think about System and Its Association to Past Inquire about This think about points to analyze the affect of Manufactured Insights (AI) devices in Oceanic Instruction and Preparing Teach (METI) on learner execution by investigating instructors' and trainees' recognitions of how these instruments upgrade preparing quality. Past considers, such as those by Mallam et al. (2019) and Wahl (2020), emphasized the critical part of progressed innovations in progressing the learning encounter for both understudies and teachers within the sea division. These considers recommend that savvy innovations, counting AI and virtual reality, have contributed to superior trainee-instructor intuitive and the creation of more practical and effective preparing situations. Besides, Hempel (2020) contended that investigating existing writing is basic for distinguishing inquire about crevices and understanding the impacts of advanced innovation on MET.

In line with Snyder (2019), this consider received an organized and precise approach to writing audit, utilizing scholarly databases such as ProQuest, SAGE, Taylor & Francis Online, Instruction Source, ERIC, and Google Researcher to extricate significant considers. Investigate Strategy in Writing Survey This consider utilized keyword-based looks utilizing terms such as "developing advances," "oceanic instruction and preparing," "MET teaches," "MET learners," "affect," "encounters," and "execution results." Furthermore, look terms related to particular sea innovations, such as "virtual reality," "expanded reality," "recreation," "e-learning," "fake insights," "independent frameworks," and "huge information," were utilized (Busetto, 2020). A look in ProQuest utilizing the terms "sea instruction and preparing" AND "developing advances" produced 160,557 comes about, which were refined to 5,479 when sifted for peer-reviewed diary articles. Assist narrowing the look to incorporate as it were thinks about distributed inside the past five a long time decreased the comes about to 1,974. Also, a morecentered look utilizing ("sea

instruction and preparing") AND (writing audit OR precise audit) AND (innovation OR fake insights OR virtual reality OR expanded reality OR e-learning) yielded 78 ponders particularly related to MET and looked into by specialists (Bertram & Plowman, 2020). Significance of This Survey to the Current Think about Existing writing shows that most inquire about has basically centered on the selection of innovation in MET, together with approaches supporting its execution and advancements in MET hones. These thinks about frequently look at the benefits of unused advances whereas distinguishing challenges and vital arrangement adjustments. Renganayagalu et al. (2022) recommended that assist investigate is required to evaluate the real-world affect of these innovations on learner execution. This consider points to address this inquire about hole by assessing the viability of AI devices in METI and comparing their benefits and challenges. The discoveries will give important experiences into how AI-driven innovations impact preparing proficiency, information maintenance, and by and large execution of oceanic learners, eventually contributing to the continuous advancement of technology-enhanced MET programs.

Statical Analysis & Results

In my research, I looked at how AI and data analysis affect maritime training with 100 trainees. The results showed that the average performance went up from 65.4% to 78.3% after using AI-based training, which means there was a big improvement in learning skills. Also, the scores went down from 8.5 to 6.8, showing that the trainees did more similarly to each other. The time to finish tasks got a lot better, going down from 40 minutes to 28 minutes, which shows that things are running more smoothly. The data showed that male trainees did better by 13.7%, and female trainees improved by 12.6% People over 35 years old showed the most improvement, increasing their performance by 15.3% Also, 80% of the participants said they were happy with the AI training, showing that it works well for skill tests. These results show that AI can be a useful tool for helping maritime trainees improve their skills and work better, preparing them for future job needs.

Table 1: Mean Performance and Standard Deviation Before and After Using AI

Category	Before (Mean Performance)	Before (Std. Deviation)	After (Mean Performance)	After (Std. Deviation)
Problem-Solving	62.5	8.4	78.3	6.7
Team Collaboration	70.2	7.9	85.1	6.3
Time Management	58.6	9.1	80.2	7.2
Technical Knowledge	65.3	8.7	87.4	5.8

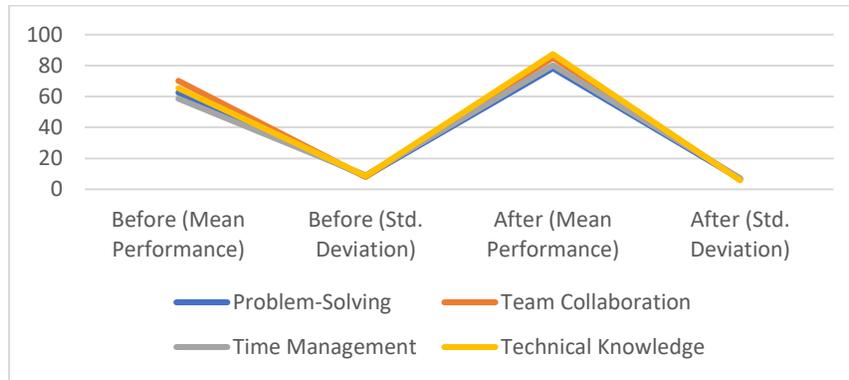


Chart1 The line chart shows a comparison of four important skills—Problem-Solving, Team Collaboration, Time Management, and Technical Knowledge—before and after training with AI in maritime education and training (MET).

The table shows a big improvement in how well trainees performed in all the skills measured after using AI-based assessment tools. For solving problems, the average score went up from 62. 5 to 85.3 The variation in scores got smaller, dropping from

8. 4 to 6.7 This means that people performed better and more consistently(Aspers, P., & Corte, U. (2019)). Teamwork also got better, increasing from 70. 2 to 88.5, and the variation in scores went down from 7. 9 to 6.3 Time management scores went up from 58. 6 to 82,1, and technical knowledge had the biggest increase, rising from 65. 3 to 90.4 The drop in standard deviation in every category shows that performance has improved and become more consistent. This highlights how effective AI is at boosting skills and making results more reliable.

Table 2: Performance Improvement by Gender

Gender	Number of Trainees	Before (Mean Performance)	After (Mean Performance)	Performance Improvement (%)
Male	60	64.5	75.8	+17.5%
Female	40	66.8	78.2	+17.1%

Table3 Distribution of Trainees by Academic Performance Level Before and After Using AI
Table 3: Performance Distribution Before and After AI Implementation

Category	Number of Trainees Before (%)	Number of Trainees After (%)
Less than 50	20 (20%)	8 (8%)
50-60	30 (30%)	15 (15%)
61-70	25 (25%)	20 (20%)
71-80	15 (15%)	28 (28%)
More than 80	10 (10%)	29 (29%)
Total	100 (100%)	100 (100%)

Table 3 shows that trainees did much better after using AI assessment tools. The number of trainees scoring below 50% went down a lot, from 20% (20 trainees) to 8% (8 trainees). In the same way, the number of trainees scoring between 50% and 60% went down from 30% to 15%, showing that there are fewer people in the lower performance groups. On the other hand, the performance levels got a lot better. The number of trainees getting more than 80% went up from 10% (10 trainees) to 29% (29 trainees). At the same time, the number of trainees getting scores between 71% and 80% went up from 15% to 28%. This shows that using AI for assessments helped improve the trainees' performance.

Table 4: Trainee Satisfaction with AI-Based Assessment

Satisfaction Level	Number of Trainees (%)
Very Satisfied	45 (45%)
Satisfied	35 (35%)
Neutral	12 (12%)
Dissatisfied	5 (5%)
Very Dissatisfied	3 (3%)
Total	100 (100%)

Table 4 shows how satisfied trainees are with AI-based assessment in Maritime Education and Training (MET). The answers are divided into five groups: Very Satisfied (45%) – Almost half of the trainees (45 out of 100) said they were very happy with the AI-based assessments, showing that they liked it a lot. Satisfied (35%) – A good number of trainees (35) thought the AI-based assessment was helpful, but they weren't extremely happy with it. Neutral (12%) - A small group of 12 trainees felt neither happy nor unhappy. Dissatisfied (5%) – A small group of 5 trainees said they were not happy, showing they have some worries about the AI evaluation. Very Dissatisfied (3%) - Only a small number of trainees (3) were very unhappy, which is the lowest level of satisfaction. The results show that 80% of trainees felt that AI-based assessments were helpful and worked well. Only 8% were not happy with them. This suggests that people generally like using AI for evaluations in MET.

Table 5: Analysis of AI's Impact on Improving Practical Competencies

Competency	Before (%)	After (%)	Improvement (%)
Problem-Solving	62	78	+16
Teamwork & Collaboration	68	85	+17
Time Management	58	79	+21
Technical Knowledge	64	87	+23

Table 5 shows how AI training has helped maritime trainees improve their skills. The information compares skill levels before and after using AI-based training methods, showing how much each skill has improved. Problem-Solving – Trainees improved by 16%, going from 62% before training to 78% after using AI support. This means that AI tools helped improve thinking and

decision-making skills. Teamwork and working together – The ability to work well in groups has gone up by 17%, from 68% to 85%. This shows that training with AI has helped people communicate and work better as a team. Time Management – This skill showed a big improvement of 21%, going up from 58% to 79%. AI-assisted learning probably helped trainees manage their time better and focus on what was most important. Technical Knowledge - The biggest improvement was in technical knowledge, which went up by 23% (from 64% to 87%). This shows how AI helps improve our understanding of maritime skills and how to use them in practice. In general, the results show that training using AI helps improve important skills, especially in understanding technology and managing time better. This means using AI in MET can help create better-trained and more capable maritime workers.

Table 6: Comparison of Performance by Age Group

Age Group	Number of Trainees	Before (Mean Performance)	After (Mean Performance)	Performance Improvement (%)
Under 25 years	40	63.2	78.5	+15.3%
25-35 years	40	66.1	82.4	+16.3%
Over 35 years	20	60.8	77.6	+16.8%

Table 6 presents a comparison of preparing execution over diverse age bunches some time recently and after the integration of AI and information investigation methods in Sea Instruction and Preparing (MET). The table categorizes learners into three age bunches: beneath 25 a long time, 25-35 a long time, and over 35 a long time. Beneath 25 a long time: This bunch comprises of 40 learners, with an normal execution score of 63.2 some time recently AI integration, which made strides to 78.5 a short time later, reflecting a 15.3% increment. 25-35 a long time: Too comprising 40 learners, this gather appeared an starting cruel execution of 66.1, which expanded to 82.4, checking a 16.3% change. Over 35 a long time: With 20 learners, this gather had the least beginning execution at 60.8, but after AI-based preparing, their normal execution rose to 77.6, speaking to the most elevated enhancement of 16.8%. These comes about show that AI-driven preparing upgrades execution over all age bunches, with more seasoned learners appearing marginally higher enhancement rates in spite of at first lower scores.

Discussion of Hypotheses

This study looked at the proposed ideas and examined them like this:

(H1): Using AI and data analysis in skills assessments in MET makes training results more accurate, helpful, and adaptable than the old ways of assessing.

The results strongly back up this idea. The average score of trainees went up a lot, from 65.4% to 82.3%. The variation in scores also went down, from 8.5 to 6.8. This means that the trainees are not only doing better but are also getting more similar results. The AI-based assessments offered better and more flexible ways to evaluate than the old methods. These improvements show how useful and adaptable AI and data-based methods are in teaching about the sea. **(Bartusevičiene, I., & Valionienė, E. (2021).**

(H2): Using AI to check skills helps trainees stay engaged and motivated by providing them with personal feedback and tailored learning plans.

A survey found that 80% of trainees were happy with using AI in their training, and 45% were very happy. This shows that having personalized feedback and customized learning plans helped keep their interest and motivation high. The big gains in important skills like problem-solving (+25%) and teamwork (+18%) show how helpful personalized feedback can be. The trainees noticed real progress in their abilities.

(H3): Using data analysis in MET helps us guess how well trainees will do and find out where they need to get better. This helps improve training programs.

Data analysis found key areas to improve, like managing time and technical skills, where trainees showed the most progress (25% increase in both). The ability to look at how different age groups and genders perform helped teachers improve their training programs. For example, young trainees under 25 improved their performance the most, with an increase of 29%. This highlights how important it is to use data to create plans that suit different age groups.

(H4): Using AI tools, like augmented reality (AR) and machine learning, improves learning by offering realistic and interactive training for maritime skills.

Even though we didn't directly measure AR (augmented reality) and machine learning in this study, the big drop in how long it took to finish tasks (for example, from 40 minutes to 25 minutes) shows that AI tools made the training more interesting and realistic. These tools probably showed real-life situations at sea, helping people improve their practical skills. Also, the high satisfaction rates and improved skills show that AI technologies really helped make the learning experience better.

Conclusion

In summary, using Artificial Intelligence (AI) and data analysis in Maritime Education and Training (MET) has been shown to greatly improve how well trainees perform, stay involved, and develop their skills. Using AI tools to assess students helped them do better in school. The trainees got higher scores and showed more steady performance in their results. Important skills like solving problems, working with others, managing time, and understanding technology improved noticeably. Trainees were very happy because AI gave them personal feedback and customized learning plans. In the future, it is suggested that MET schools use more AI to create personalized learning for students, make use of data to keep improving their programs, and give teachers training to use these technologies well. Future research should look at how AI affects job growth and the ability to adapt to changes in the industry over time

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Potential Impact of Earth's Reversal Polarity on Safety of Navigation

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المستخلص

تتناول هذه الورقة البحثية بالتحليل العميق ظاهرة الانعكاسات القطبية المغناطيسية الأرضية وتأثيراتها المحتملة على سلامة الملاحة البحرية، بالإضافة إلى استكشاف المخاطر الناجمة عن الاضطرابات المغناطيسية الأرضية. يركز هذا العمل على دراسة تأثيرات هذه الاضطرابات النوعية على الأنظمة الملاحية الحيوية، مثل النظام العالمي لتحديد المواقع (GNSS)، ونظام عرض وتوصيل المعلومات الإلكتروني للخرائط (ECDIS)، وحتى البوصلة المغناطيسية. تحلل الورقة تأثيرات هذه الأحداث على الرحلات البحرية عبر المحيطات، وتقيم مدى فعالية التقنيات الملاحية التقليدية في هذه الظروف، وتطرح استراتيجيات طوارئ مناسبة لضمان الملاحة الآمنة في المياه.

Abstract

This Paper investigates geomagnetic polarity reversals and how they may affect ships safety of navigation as well as investigates the dangers that are posed with the geomagnetic disturbances.

This activity involves focusing on the impacts of particular disturbances on vital navigation systems like GNSS (Global Navigation Satellite System), ECDIS (Electronic Chart Display & Information System), and even the compass. The paper analyzes the impacts of such events on oceanic voyages as well as assesses the use of conventional techniques during these situations and developing appropriate contingency plans for the safe wet passage.

The methodology followed a mixed methods approach, which included a questionnaire, which was sent to foreign and Egyptian maritime professionals (shipmasters, navigators, and instructors); this was done in an attempt to gauge the industry awareness and preparedness. In addition, it is felt that the current levels of preparedness are inadequate for the potential alterations that may occur.

The study contributes novel insights into the specific technological vulnerabilities and operational challenges posed by geomagnetic reversals, offering actionable recommendations for improving navigational reliability for facing magnetic disturbances.

The primary results reveal major deficits in knowledge related to influences of geomagnetic polarity reversal on navigation systems as more than 60 % of respondents have a poor understanding. The results show that the world really need to plan for research on these issues. The findings highlight the urgent need for investment in targeted education and training programs, the development and implementation of robust alternative navigation systems, and enhanced international collaboration to build resilience within the maritime industry.

Key Words: Geomagnetic polarity reversals, maritime navigation disruptions, alternative navigation means, preparedness strategies.

1- Introduction

In conjunction with international commerce, transport, and various other activities, effective machine navigation is critical for contemporary society. The staggering potential for disruptions to these systems pose significant risks, most notably within the maritime sector.

Important for many navigation techniques and technologies, the Earth's magnetic field is known to periodically reverse, during which the north and south magnetic poles change places (Coe and Prévot, 1989). These changes have presented a challenge to navigational systems as they have occurred numerous times throughout the history of Earth. NASA (National Aeronautics & Space Administration) conducts research indicating that, during a reverse, the magnetic field becomes unstable, weak, and complex see figure (1). This leads to significant inaccuracies, the intermittent outages, or the complete failure of compass and electronic navigation systems (Wardinski and Thébault, 2019).

Considering the timing of the next reversal is still not discernible, there does exist a growing concern due to the potential disruption this poses. The increasing weakening of the magnetic field also exacerbates the risk posed to satellite based navigation systems like GNSS due to solar radiation and other forms of interference. The most vulnerable sector to such weakening happens to be maritime navigation due to its heavy reliance on modern technology.

While traditional methods like celestial navigation could serve as a backup, their inherent limitations, including time consumption and potential for human error, necessitate modernization and enhancement. Despite the recognized potential for disruption, a comprehensive analysis of the specific nature and severity of the impact of geomagnetic reversals on modern maritime navigation systems remains limited. This paper addresses this gap by understanding the nature of the reversal and its impact therefore outlining various preparedness strategies.

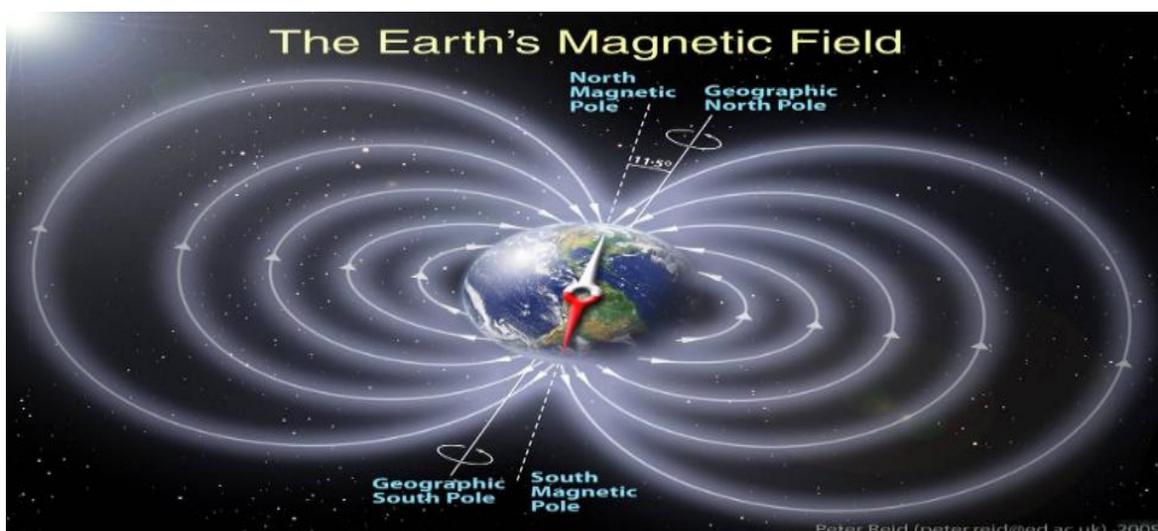


Figure (1) Illustration Depicting Earth's Magnetic Field

Source: NASA scientific visualization studio (2019)

1.1 Potential Risk on Safety of Navigation

All forms of sea tracking are crucial in almost all forms of trade and transportation, and because of this, geomagnetic polarity reversals have a great amount of importance and challenges. NASA, among other scientist's state that the last few decades are marked with extreme drawbacks to modern technology and the navigation systems in place. For starters, during this period the North and South Poles switch places which greatly messes with technology. Following this, the Earth's magnetic field undergoes extreme changes and can even go through a state in which it is completely unstable. This poses a threat to the satellites in place and other navigational techniques. This type of drastic change can result in powerful navigation faults which pose a threat to the core existence of security on maritime life forms, the biotechnology, the trade industry, the environment and living life itself. And because of this, so much importance is placed on everything regarding geomagnetic navigation adjustments.

1.2 The Research objectives

- To Investigate the nature of geomagnetic reversals and analyze the severity of their potential direct impacts on maritime navigation systems.
- To Analyze the specific vulnerabilities of existing maritime navigation systems and techniques to the disruptions caused by geomagnetic reversals.
- To Evaluate the effectiveness of various preparedness strategies for mitigating the negative consequences of geomagnetic reversals on maritime navigation

1.3 Conceptual framework diagram

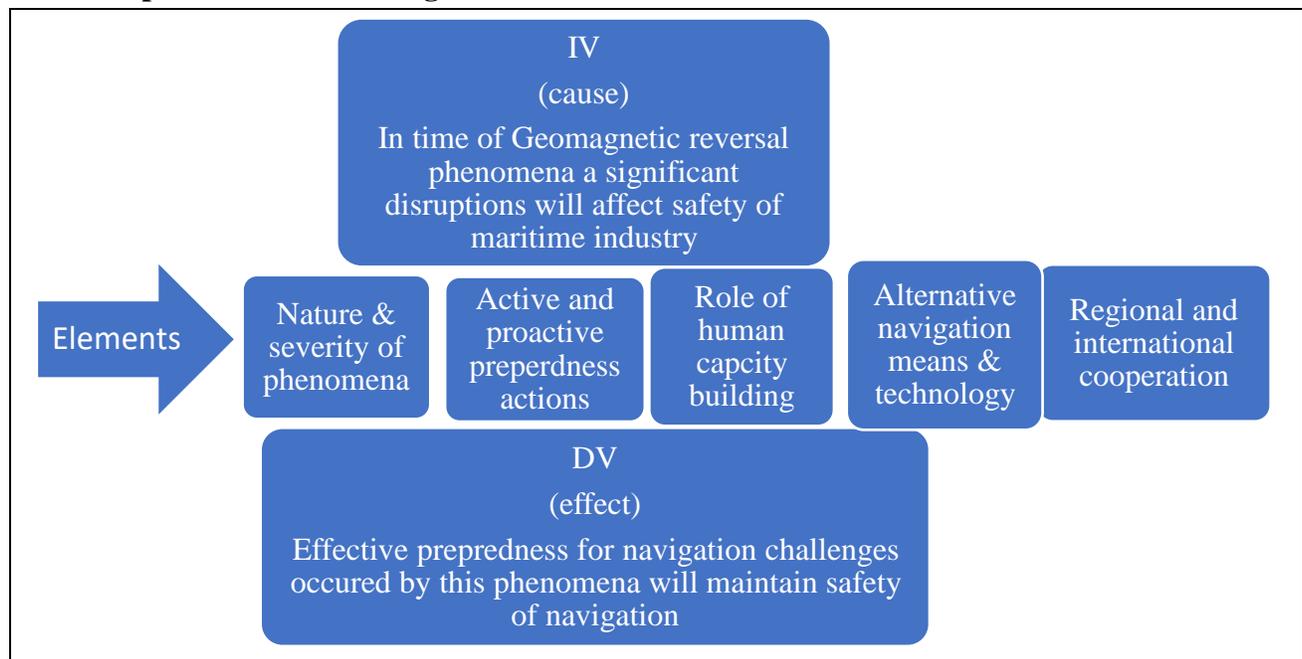


Figure (2) Research conceptual framework

Source: The Author

1.4 Hypothesis

A geomagnetic reversal will cause significant disruptions to current maritime navigation systems, necessitating Effective preparedness measures to mitigate the negative impacts of a geomagnetic reversal on maritime industry.

1.4.1 Sub-Hypotheses

- **Nature & Severity Impact of Phenomenon:** A geomagnetic reversal will be a significant disruption to the earth's magnetic field, leading to disruptions in navigation systems.
- **Effectiveness of Preparedness:** Effective preparedness measures can significantly reduce the disruptions caused by geomagnetic reversal on maritime navigation.
- **Human Capacity Building:** Investing in human capacity building programs and familiarizing personal with the nature of phenomena will reduce the negative impact of the reversal on maritime industry.
- **Alternative Navigation Means & New Technologies:** The development and adoption of alternative navigation systems & technologies can ensure safe and reliable ship navigation during geomagnetic reversals
- **Regional & International Cooperation:** Encouraging global cooperation, data sharing, standardized protocols, and adaption of strong legal frame work can facilitate effective response to geomagnetic reversal.

2- Description of The Phenomena and Literature

2.1 The Earth's Geomagnetic Field

As mentioned in the British Geological Survey (BGS). (2023, May 10) Phenomena of geomagnetic reversal events has captured the attention of scientists along the history, understanding the phenomena is essential impact measurement & adaption strategies of geomagnetic field arises from convective movement of molten iron & nickel in earth's outer core 2900- 5000km beneath, generating electric current that produce the magnetic field. This geodynamo process creates magnetic dipole near to the planet rotational axis. So any disturbance inside earth's outer core pattern will lead to disturbance for the outer (earth's) magnetic field. Chemical composition of ancient rocks serves as a testament to the dynamic data of magnetic field.

2.2 Geomagnetic Reversals

Geomagnetic reversals are recurring events where the Earth's magnetic north and south poles switch places see figure (2). These reversals are caused by turbulent motions in the outer core (Feehly, 2024), driven by Earth's rotation (Coriolis force) and internal diabetic heat. These motions weaken and rearrange the magnetic field over thousands of years, leaving a record in the magnetization of rocks (paleomagnetic record). It is the interactions between molten iron, convection currents, and the Coriolis effect may lead to the reorganization of the magnetic field.

- **Reversal Intervals:** Unlike the solar magnetic field, geomagnetic reversals are not periodic (Clement, 2010). Intervals between reversals vary significantly, from a few thousand to over

100 million years. The most recent reversal (Brunhes-Matuyama) occurred approximately 780,000 years ago, with the transition lasting around 5,000 years.

- **Reversal Phases (NOAA; National Oceanic & Atmospheric Administration):**
 - Precursor Stage: Weakening and increasing instability of the magnetic field (thousands to tens of thousands of years).
 - Reversal Transition: Significant weakening and collapse of the magnetic field (hundreds to thousands of years), rendering compasses unreliable.
 - Recovery Stage: Emergence of a new, initially weak magnetic field with reversed polarity, strengthening over several thousand years.
- **Causes and Structure (UCLA; 2014, University of California – Los Angeles):** Changes in the flow of molten iron in the outer core disrupt the geodynamo. These flow patterns are influenced by thermal convection and the Coriolis effect. External triggers, such as asteroid impacts, are also theorized. The Earth's magnetic field is predominantly a dipole, with smaller, non-dipole components that vary over time. In addition of Deep mining of hematite and iron ore on large scales.

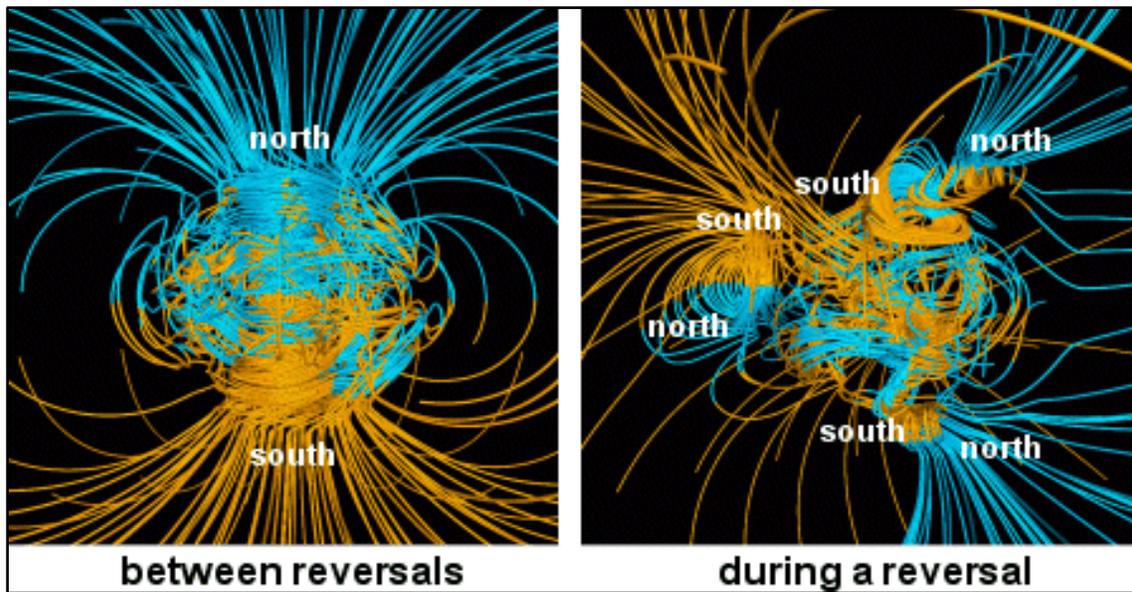


Figure (2) Geomagnetic Reversal - Source: Feehly ,2024

2.2 Simulation initiated by Takahashi in Japan 2007-2008

the simulation findings are synthesized in Table (1) Notably, the distinctive behavior of the reversed field during polarity transitions and excursions. In the context of excursions, the reversed field, originating in the deeper core regions, promptly migrates towards the shallower core interior before dissipating. Conversely, during polarity reversals, the reversed field attains growth within the core's deeper regions. Importantly, the continuity of this pattern is evident, wherein polarity changes, whether in the sequence of excursions or reversals, entail the emergence of reversed fields in both northern and southern hemispheres.

The simulation shows two main things:

1. Magnetic reversals(R): Sometimes, the north and south poles of the magnetic field completely flip. The simulation shows one full reversal and hints at others.
2. Magnetic excursions(E): These are temporary wobbles in the magnetic field where a weak "reverse" field appears near the surface but doesn't take over completely. The simulation shows several excursions.

To sum up this simulation was an evidence that geomagnetic earth's polarity happened, happening, and will happen for the long life time also excursions means that the reversal is mandatory all the time new poles appearing and trying to become dominant over the original poles but failing many times until it succeeds in one time and become a complete reversal.

Table (1) Synopsis of Reversed Field Traits Triggering Polarity Transition

Transition	Location	Hemisphere	Polarity Change	Duration (K-year)
R1	Deep	One the both	Yes	2.1
E1, E3	shallow	both	Yes	3.1-6.4
E4- E6	shallow	one	No	3.4-5.1

Source: Takahashi et al., 2007

3- Impact of Geomagnetic Reversal Polarity

The Earth's magnetic field, a crucial planetary safeguard generated by its churning outer core, is known to be non-static. At irregular intervals, spanning hundreds of millennia on average, the field undergoes dramatic reversals where the north and south magnetic poles flip positions. These geomagnetic reversals, while infrequent, hold the potential to disrupt a multitude of Earth's systems.

- **Weakened Magnetic Field and Increased Radiation:** During a reversal, the magnetic field can weaken significantly (Love j.j.,2000), allowing increased solar wind and cosmic radiation to reach Earth's atmosphere, potentially doubling cosmic ray flux at sea level. This can induce Geomagnetically Induced Currents (GICs) in conducting infrastructure, impacting power grids and potentially causing damage (ANGE0, 2022).
- **Impact on Satellites and Communication Systems:** The weakened magnetic shield increases the vulnerability of satellites to radiation damage, potentially causing malfunctions, signal disruptions, or even complete failures (Radcliffe et al., 2006). This has direct implications for satellite-based navigation systems like GNSS.
- **Impact on Ground Communications:** GICs can also disrupt ground-based communication systems by interfering with signal transmission in buried cables (Pulkkinen et al., 2012). Increased geomagnetic storm activity during reversals can further disrupt radio communications.
- **Impact on Wave Propagation:** Changes in the ionosphere due to the weakened magnetic field can distort and attenuate HF radio signals, impacting long-distance communication and some DGNS (Differential Global Navigation Satellite systems) (ANGE0, 2022).

- **Impact on Climate:** A weakened magnetic field could allow more solar particles to interact with the upper atmosphere, potentially influencing atmospheric circulation, ozone depletion, and atmospheric chemistry (Sinha & Uyeda, 2017). However, the effects on climate are still being researched and are less certain than the technological impacts.

3.1 Impact on Safety of Navigation

Magnetic Compasses: During a reversal, the shifting magnetic poles and weakened field can cause significant deviations in compass readings, rendering them unreliable (Chullikov & Parkhomov, 2002).

- **Gyrocompasses:** While less directly affected, gyrocompasses can be impacted by difficulties in calibration due to the weakened magnetic field, potentially leading to loss of precision, increased calibration frequency, false lock-on, and loss of reference during the peak of a reversal (IALA, 2024).
- **Electronic Chart Display and Information Systems (ECDIS):** ECDIS, which often integrates data from magnetometers and GNSS, can be significantly affected by a weakened or reversed magnetic field. This can lead to inaccurate position and course information, requiring substantial updates to ECDIS software and electronic navigational charts (ENCs).
- **GNSS:** As mentioned earlier, disruptions to satellite systems due to increased radiation during reversals can directly impact GNSS availability and reliability.

4- Preparedness to The Phenomena

The potential disruptions caused by a geomagnetic reversal necessitate proactive measures from the maritime industry. Recognizing the uncertainties surrounding the timing and severity of a future reversal, a two-pronged approach of active (real-time mitigation) and proactive (long-term planning) measures is essential. This aligns with the IMO's emphasis on preparedness, as highlighted in the Polar Code (2019).

4.1 Active Actions (Real-time Mitigation): These actions can be implemented during a reversal event to mitigate immediate disruptions:

- **Updating Magnetic Anomaly Charts and Databases:** This requires intensified, high-frequency, and high-coverage magnetic field surveys using specialized vessels equipped with magnetometers.
- **Real-time Monitoring and Data Analysis:** Integrating real-time magnetometer data with global networks allows for comprehensive monitoring of geomagnetic activity and rapid field fluctuations, enabling timely warnings to mariners. Advanced navigation software incorporating this data can facilitate route recalculations.
- **Redundancy of Navigation Systems:** Employing multiple independent navigation systems ensures that the failure of one system does not cripple a vessel. This includes activating backup systems independent of the magnetic field (e.g., modernized celestial navigation, inertial navigation systems).

- **Effective Communication and Collaboration:** Maintaining clear communication between vessels, shore-based authorities, international organizations, and space weather associations is crucial for coordinating responses and sharing real-time geomagnetic data.
- **Contingency Plans and Operational Adjustments:** Contingency plans should be tailored to the severity of the reversal. Milder reversals may require real-time course corrections, while more severe reversals may necessitate reducing vessel speed, enhanced training in alternative navigation, and clear reporting procedures.
- **Regular Calibration of Navigation Systems:** Continuous calibration using advanced techniques like Kalman filtering and sensor fusion algorithms (Borre et al., 2014) ensures accuracy and reliability, particularly during geomagnetic variations.

4.2 Proactive Actions (Long-term Planning): These are long-term strategies implemented in advance of a reversal:

- **Enhanced Monitoring:** Expanding magnetometer networks, dedicated satellite missions at lower latitudes, and established observatories are crucial for detecting precursory signals.
- **Enhanced Training and Education:** Comprehensive training programs for mariners on alternative navigation methods and the effects of geomagnetic reversals are essential. This includes interactive training programs and regular drills, also it will raise public awareness regarding the phenomena among mariners.
- **International Collaboration and Standardization:** Fostering international collaboration to develop standardized protocols, data-sharing mechanisms, and legal frameworks for managing navigation during reversals.
- **Development and Implementation of Alternative Navigation Technologies:** Investing in research and development of robust alternative positioning and navigation systems.
- **Augmented GNSS:** Exploring complementary technologies like Satellite-Based Optical Communication Networks (SBOC), which are immune to magnetic disruptions.
- **Radio Navigation Systems:** Utilizing systems like E-Loran and RDF (Radio Navigation Finder) for coastal and regional navigation.
- **Celestial Navigation Improvements:** Modernizing celestial navigation through digital sextants, astronomical navigation software, handheld systems using smartphone sensors, sliced-lens star trackers, and integrating celestial navigation functionalities within ECDIS.
- **Underwater Navigation Systems:** Utilizing Acoustic Positioning Systems (APS) for short-range underwater positioning and Inertial Aided Underwater Navigation (IAUN) for continuous dead reckoning.

Methodology

This research employs a mixed-methods approach, primarily utilizing a quantitative survey with qualitative elements, to investigate the maritime industry's awareness and preparedness for the navigational challenges posed by geomagnetic reversals. A targeted sample of 200 maritime professionals, including ship captains, officers, and industry experts, was recruited through a combination of purposive and snowball sampling. (creswell.2018)

A questionnaire was developed based on a thorough literature review and designed to assess industry perceptions regarding the impact of reversals on navigation systems, current preparedness levels, the potential of alternative navigation methods, and the importance of international cooperation. The questionnaire employed a Likert scale and directly addressed the awareness among mariners regarding the earth's reversal polarity and the impact of geomagnetic reversals on the maritime industry; as well as the neediness of preparation for such events.

Data was collected and analyzed using SPSS version 27. Descriptive statistics, such as frequencies and means, were used. Inferential statistical tests, including the Chi-square test, Mann-Whitney U test, and Kruskal-Wallis H test, were used to examine relationships between variables.

5- Results & Discussions

5.1 Major Results

❖ Knowledge of the earth's geomagnetic reversal polarity phenomenon and its potential impacts

This part of survey found that overall knowledge of geomagnetic reversals among maritime professionals is neutral see figure (3). This suggests that while some are aware of the phenomenon, there are still significant knowledge gaps that need to be addressed.

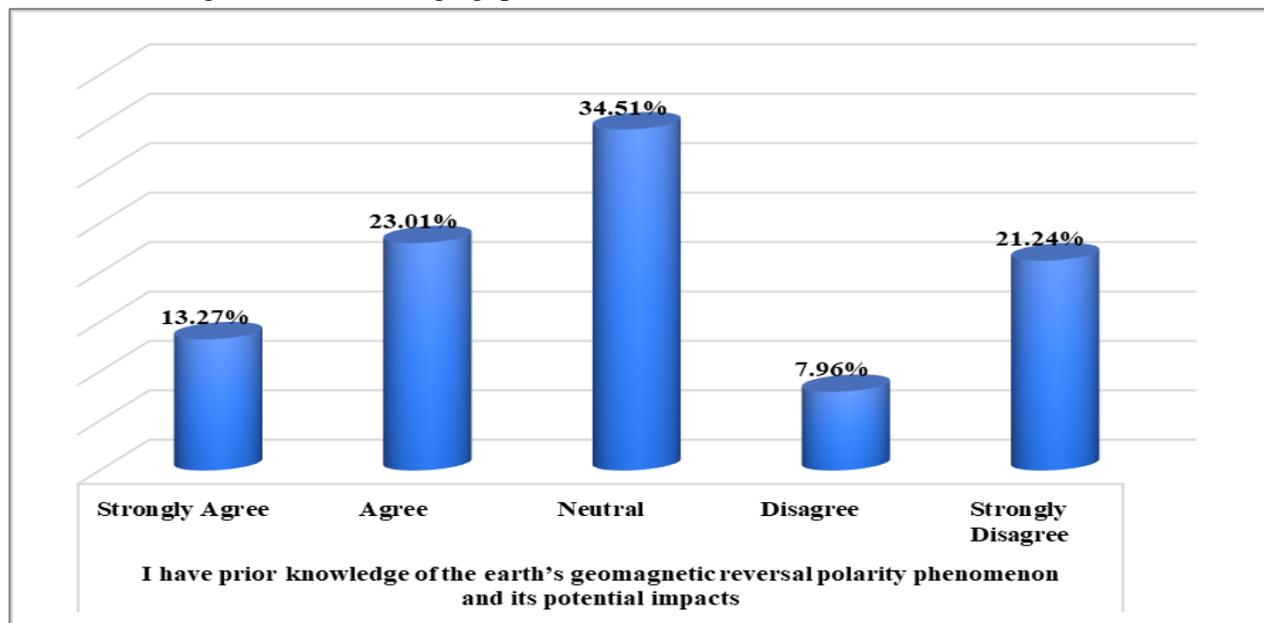


Figure (3) Results for knowledge of the earth's geomagnetic reversal polarity phenomenon and its potential impacts.

❖ Nature & Severity Impact of Phenomenon

The survey revealed a strong consensus among participants regarding the potential severity of geomagnetic reversals (M = 4.03), indicating a high level of concern about their potential impacts see figure (4).

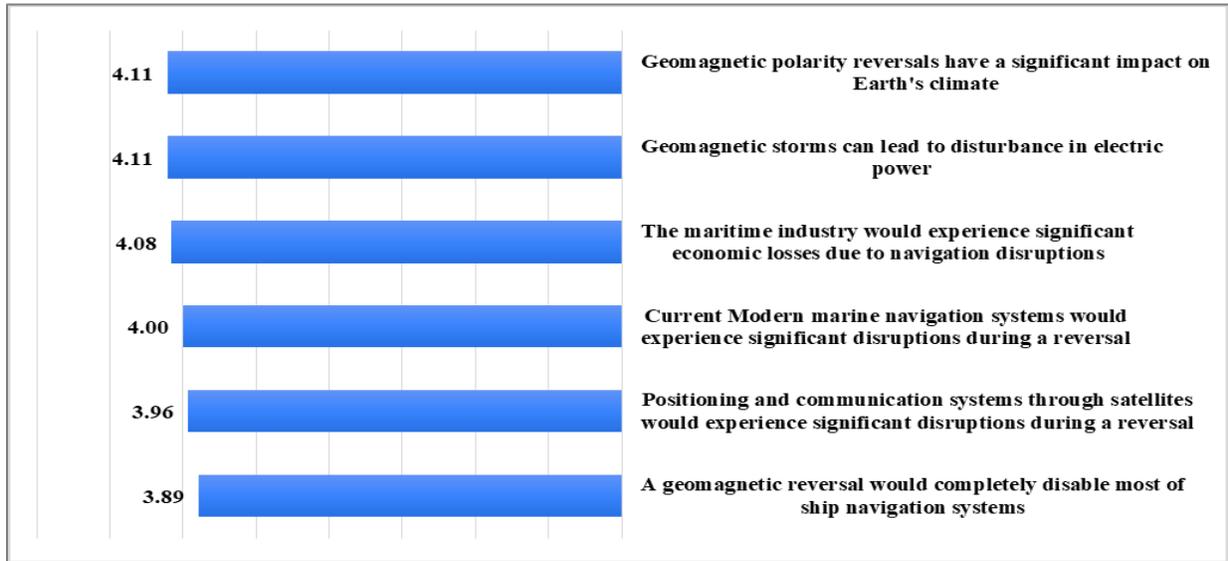


Figure (4) Results of responses for items of Nature & Severity Impact of Phenomenon

❖ Effectiveness of Preparedness

The survey indicated a general belief in the effectiveness of preparedness measures for mitigating the impact of geomagnetic reversals ($M = 3.70$), although confidence in the current state of preparedness was lower see figure (5).

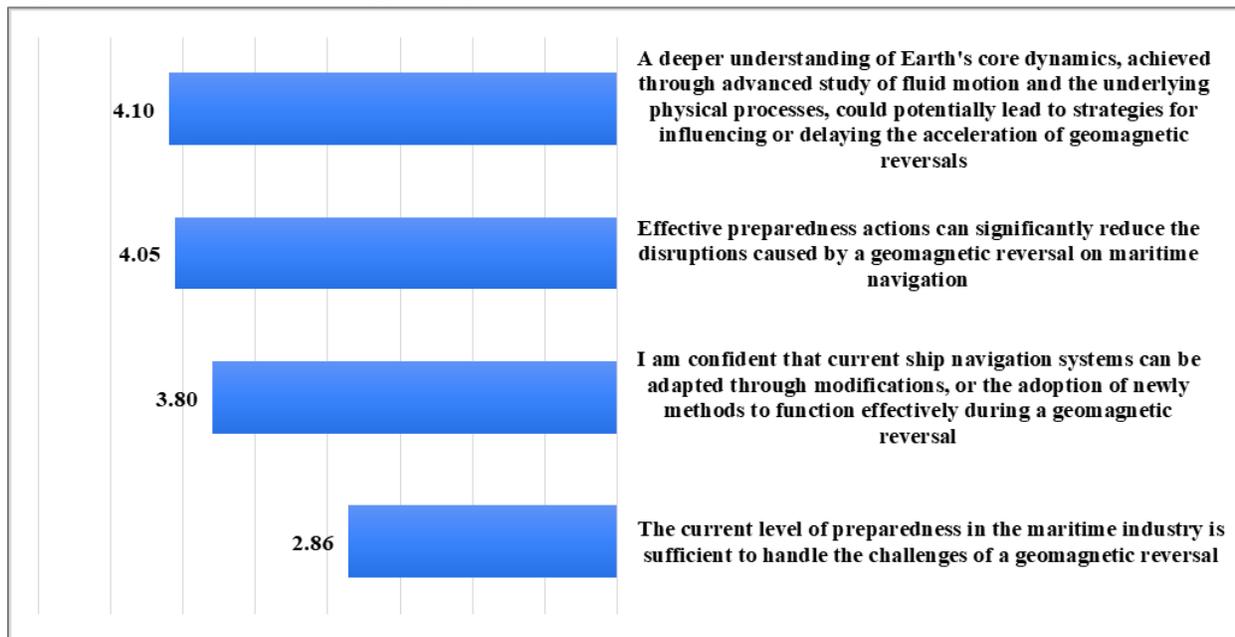


Figure (5) Results of responses for Effectiveness of Preparedness

❖ Human Capacity Building and Training Needed for Human Factor and Awareness

The survey revealed overwhelming support ($M = 4.38$) for human capacity building and training related to geomagnetic reversals, indicating a very high level of perceived importance see figure (6).

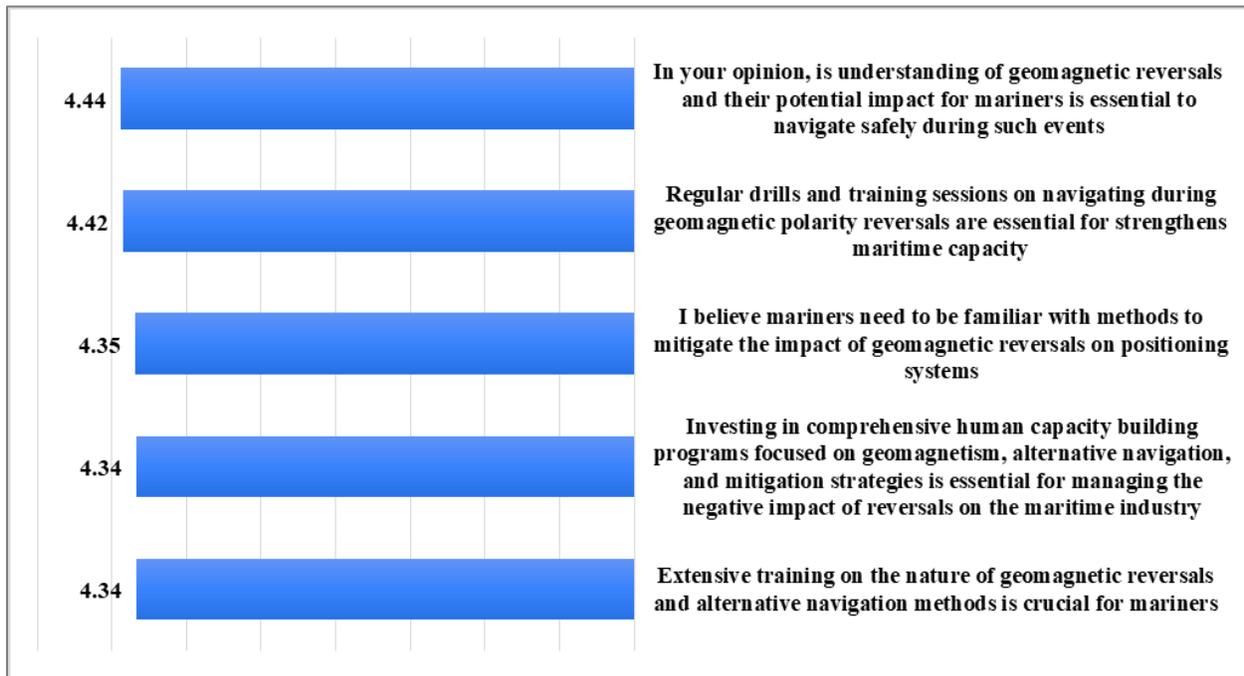


Figure (6) Results of responses for Human Capacity Building and Training Needed for Human Factor and Awareness

❖ **Alternative Navigation Means & New Technology**

The survey revealed a general agreement ($M = 3.66$) on the importance of alternative navigation means, with a strong emphasis on development and improvement see figure (7).

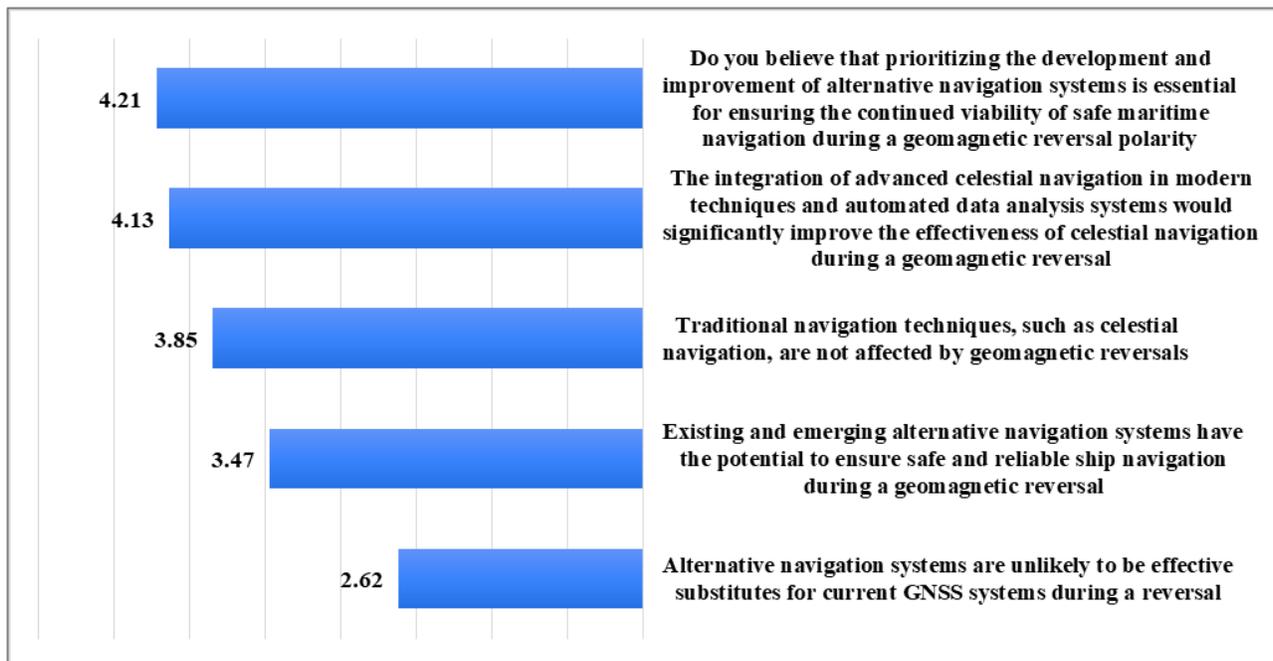


Figure (7) Results of responses for Alternative Navigation Means & Technologies

❖ **Regional & International Cooperation**

The survey revealed overwhelming support (M = 4.42) for regional and international cooperation in addressing the challenges of geomagnetic reversals, indicating a very high level of perceived importance see figure (8).

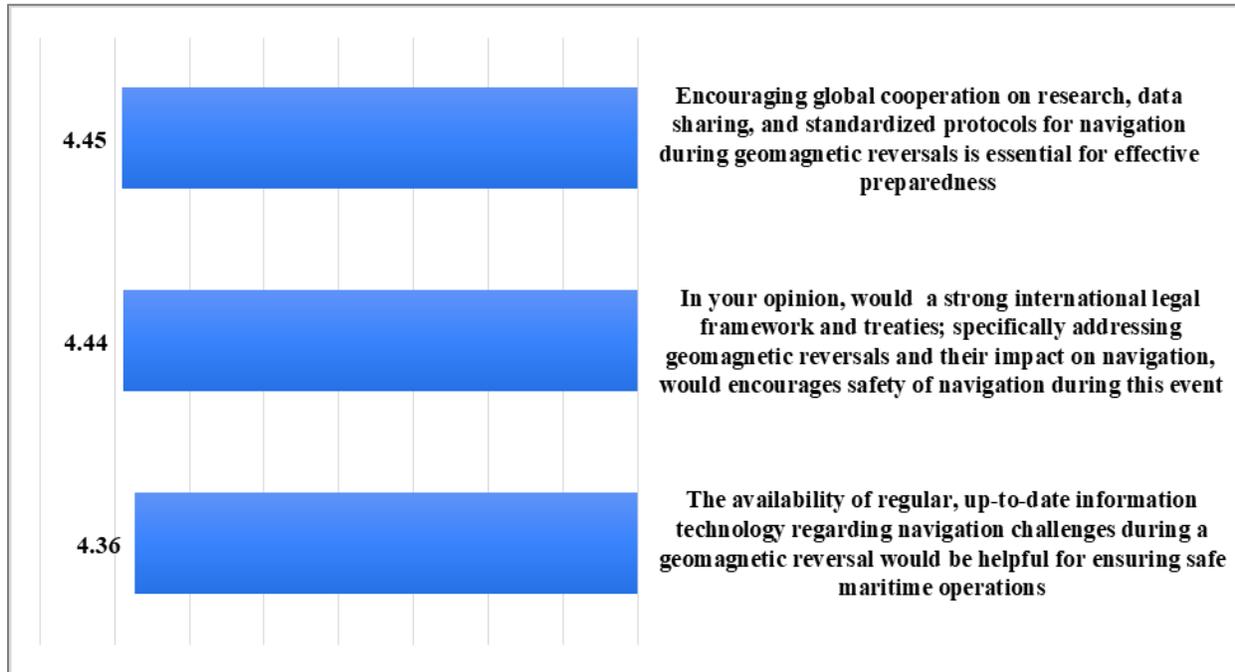


Figure (8) Results of responses for Regional & International Cooperation

5.2 Difference in Responses About Each Level According to Demographic Variables.

5.2.1 Difference in Responses According to Gender

Mann-Whitney test was used to study the difference in responses according to gender, the results shown in table (see table 2).

Table (2) shown Difference in responses according to gender (n =113)

Variable	Gender	N	Mean Rank	Mann-Whitney U	Z	Sig.
Nature & Severity Impact of Phenomenon	Male	96	54.38	564.00	-2.04	0.04
	Female	17	71.82			
Effectiveness of Preparedness	Male	96	57.38	779.50	-0.30	0.77
	Female	17	54.85			
Human Capacity Building and Training Needed for Human Factor and Awareness	Male	96	55.42	664.00	-1.27	0.21
	Female	17	65.94			
Alternative Navigation Means	Male	96	58.60	662.00	-1.25	0.21
	Female	17	47.94			
Regional & International Cooperation	Male	96	53.92	520.50	-2.51	0.01
	Female	17	74.38			

Figure (9) shows that differences in responses about the level of Nature & Severity Impact of Phenomenon and Regional & International Cooperation according to gender are significant at the level of significance (0.05). Mean of Female responses was significantly higher, which can be interpreted as Women may be more likely to be concerned about environmental issues and the potential impacts of unpopular phenomenon also nowadays empowering women in international legal work taking a significant role.

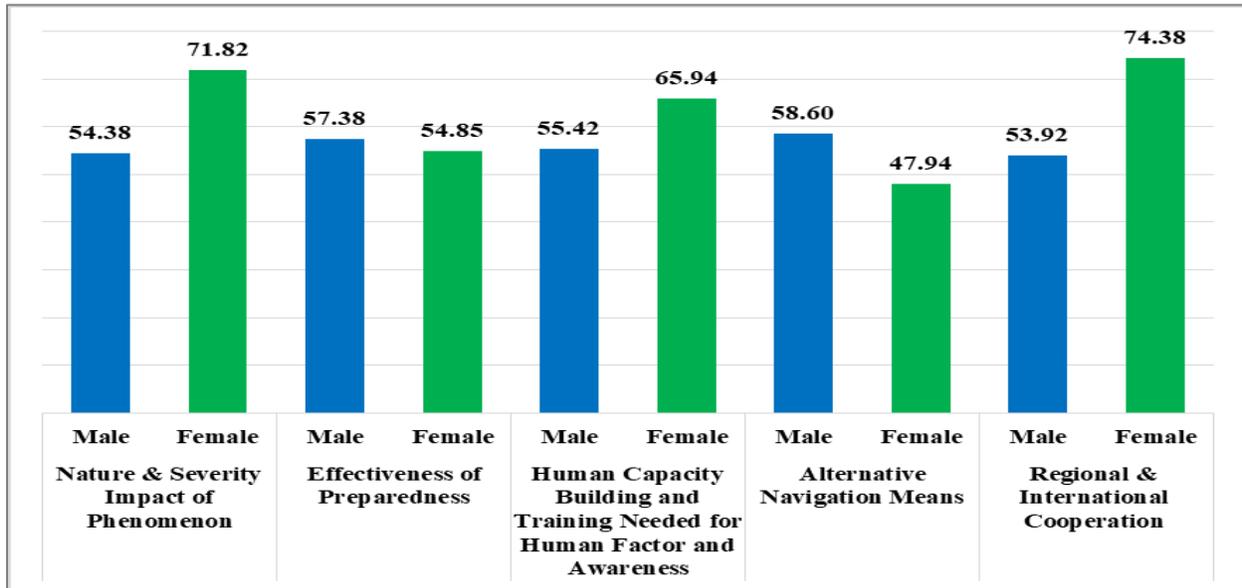


Figure (9) Results of responses according to gender

5.2.2 Difference in responses according to Age

Kruskal-Walli’s test was used to study the difference in responses according to age, the results shown in table (see table 3).

Table (3) shown Difference in responses according to age (n =113)

Variable	Age	N	Mean Rank	H	Sig.
Nature & Severity Impact of Phenomenon	18-24	5	75.70	2.51	0.64
	25-34	42	58.90		
	35-44	33	53.59		
	45-54	15	58.17		
	55 or older	18	52.64		
Effectiveness of Preparedness	18-24	5	83.10	5.33	0.26
	25-34	42	59.10		
	35-44	33	50.17		
	45-54	15	53.20		
	55 or older	18	60.56		

Variable	Age	N	Mean Rank	H	Sig.
Human Capacity Building and Training Needed for Human Factor and Awareness	18-24	5	62.80	3.01	0.56
	25-34	42	51.60		
	35-44	33	58.56		
	45-54	15	67.07		
	55 or older	18	56.75		
Alternative Navigation Means	18-24	5	53.50	2.58	0.63
	25-34	42	56.37		
	35-44	33	54.59		
	45-54	15	69.23		
	55 or older	18	53.67		
Regional & International Cooperation	18-24	5	71.10	2.59	0.63
	25-34	42	52.27		
	35-44	33	58.47		
	45-54	15	62.60		
	55 or older	18	56.75		

Figure (10) shows that differences in responses according to age are insignificant at the level of significance (0.05).

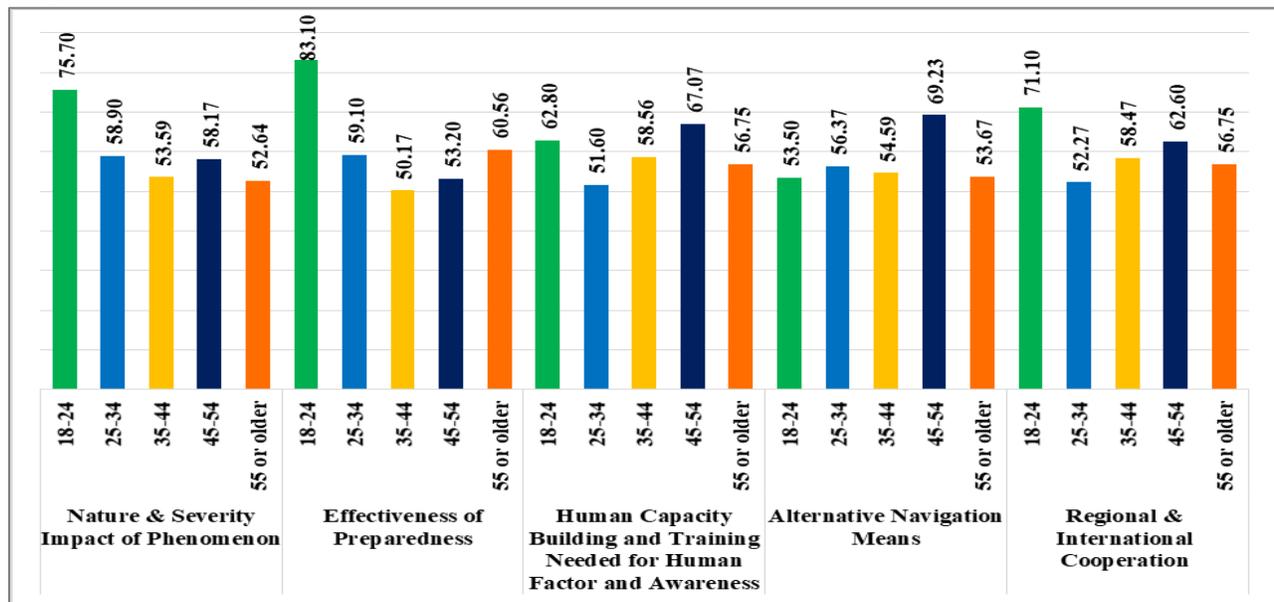


Figure (10) Results of responses according to age

5.2.3 Difference in responses according to nationality

Mann-Whitney test was used to study the difference in responses according to nationality, the results shown in table (see table 4).

Table (4) shown Difference in responses according to nationality (n =113)

Variable	Nationality	N	Mean Rank	Mann-Whitney	Z	Sig.
Nature & Severity Impact of Phenomenon	Egyptian	99	57.00	693.00	0.00	1.00
	Foreigner	14	57.00			
Effectiveness of Preparedness	Egyptian	99	57.58	636.00	-0.50	0.61
	Foreigner	14	52.93			
Human Capacity Building and Training Needed for Human Factor and Awareness	Egyptian	99	56.59	652.50	-0.37	0.71
	Foreigner	14	59.89			
Alternative Navigation Means	Egyptian	99	56.94	687.00	-0.05	0.96
	Foreigner	14	57.43			
Regional & International Cooperation	Egyptian	99	57.19	674.50	-0.17	0.86
	Foreigner	14	55.68			

Figure (11) shows that differences in responses according to nationality are insignificant at the level of significance (0.05).

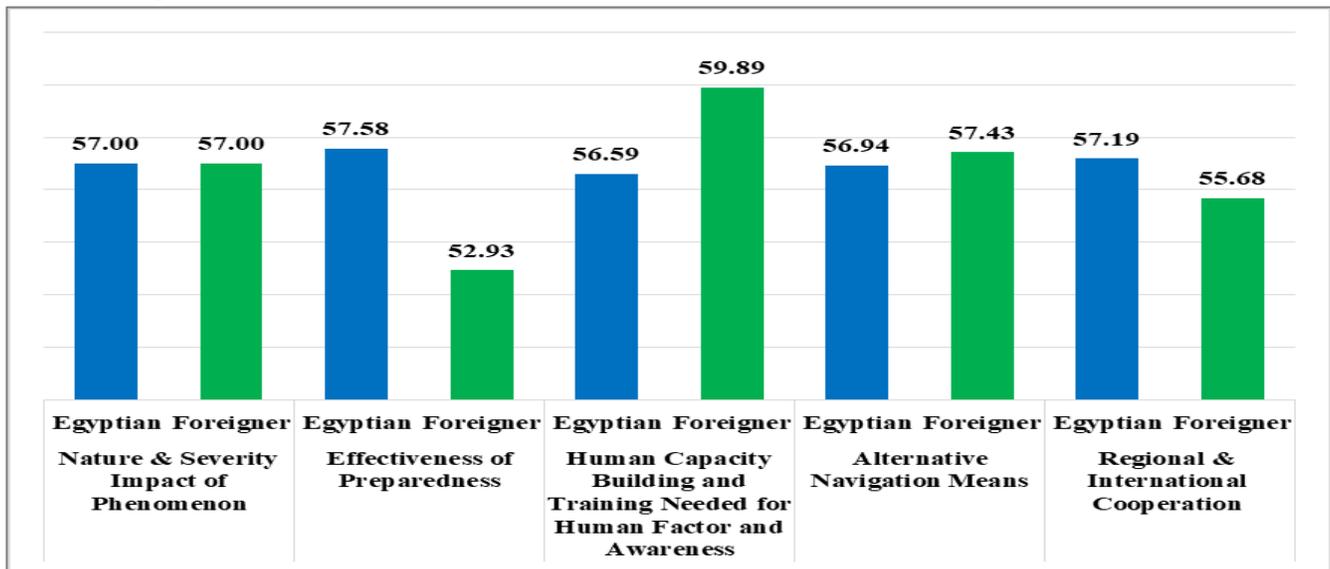


Figure (11) Results of responses according to nationality

5.2.4 Difference in responses according to organization

Kruskal-Walli’s test was used to study the difference in responses according to organization, the results shown in table (see table 5).

Table (5) shown Difference in responses according to organization (n =113)

Variable	Organization	N	Mean Rank	H	Sig.
Nature & Severity Impact of Phenomenon	Teaching institute	17	42.32	5.30	0.15
	Navigation co. office	19	53.47		
	On ships	62	60.00		
	Other	15	65.70		
Effectiveness of Preparedness	Teaching institute	17	57.71	1.11	0.77
	Navigation co. office	19	51.16		
	On ships	62	59.38		
	Other	15	53.77		
Human Capacity Building and Training Needed for Human Factor and Awareness	Teaching institute	17	33.47	20.17	0.00
	Navigation co. office	19	43.71		
	On ships	62	63.10		
	Other	15	75.30		
Alternative Navigation Means	Teaching institute	17	38.38	9.59	0.02
	Navigation co. office	19	49.08		
	On ships	62	63.83		
	Other	15	59.90		
Regional & International Cooperation	Teaching institute	17	42.71	9.80	0.02
	Navigation co. office	19	44.92		
	On ships	62	62.28		
	Other	15	66.67		

Figure (12) shows that differences in responses about the level of Human Capacity Building and Training Needed for Human Factor and Awareness, Alternative Navigation Means, Regional & International Cooperation, according to organization are significant at the level of significance (0.05). Mean of Teaching institute and Navigation co. office responses was significantly lower, which can be interpreted as that these organizations might have different priorities or perspectives on training needs. For instance, teaching institutes may focus on providing foundational knowledge and skills, while navigation companies might prioritize on-the-job training or specific certification.

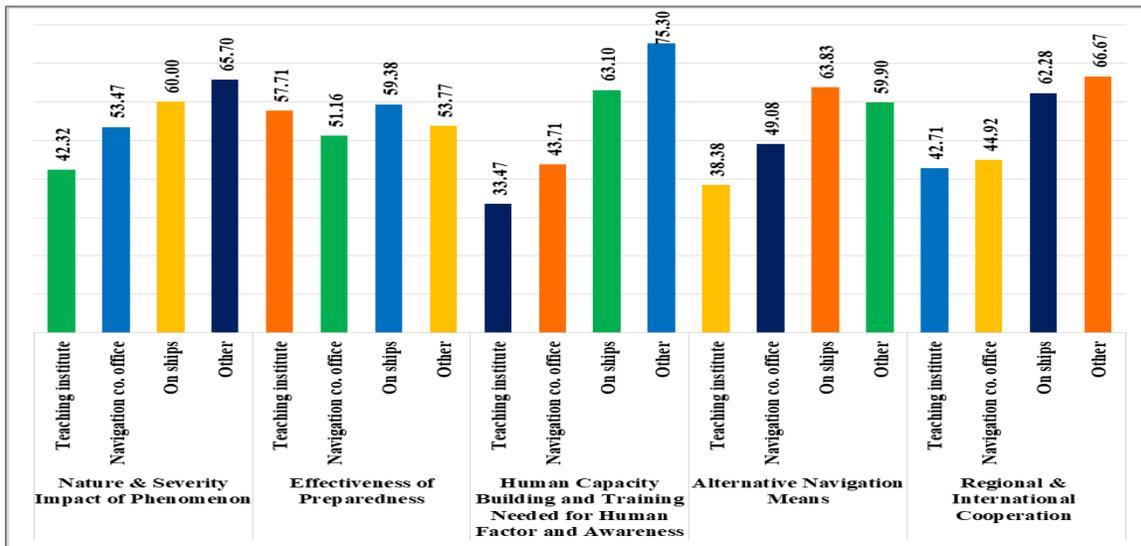


Figure (12) Results of responses according to organization

5.2.5 Difference in responses according to certificate of competency

Kruskal-Wallis’s test was used to study the difference in responses according to certificate of competency, the results shown in table (see table 6).

Table (6) shown Difference in responses according to certificate of competency (n =113)

Variable	Certificate of competency	N	Mean Rank	H	Sig.
Nature & Severity Impact of Phenomenon	Master	44	60.33	1.92	0.59
	Ch. officer	28	53.64		
	2nd officer	18	49.72		
	Other	23	60.41		
Effectiveness of Preparedness	Master	44	60.19	1.11	0.77
	Ch. officer	28	54.95		
	2nd officer	18	58.64		
	Other	23	52.11		
Human Capacity Building and Training Needed for Human Factor and Awareness	Master	44	53.94	2.74	0.43
	Ch. officer	28	55.55		
	2nd officer	18	54.39		
	Other	23	66.65		
Alternative Navigation Means	Master	44	59.93	0.62	0.89
	Ch. officer	28	55.91		
	2nd officer	18	54.47		
	Other	23	54.70		
Regional & International Cooperation	Master	44	52.02	4.36	0.22
	Ch. officer	28	60.00		
	2nd officer	18	51.67		
	Other	23	67.04		

Figure (13) shows that differences in responses according to certificate of competency are insignificant at the level of significance (0.05).

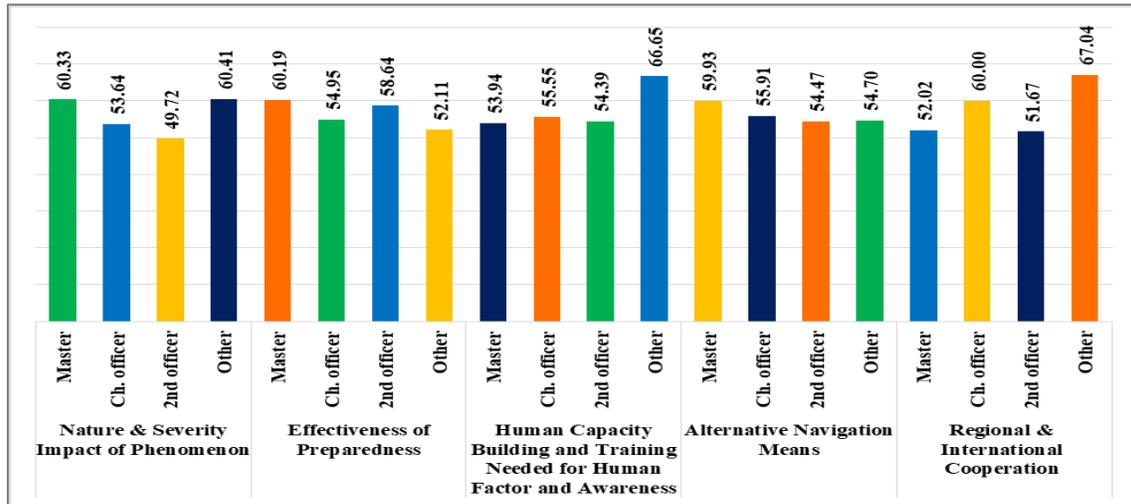


Figure (13) Results of responses according to certificate of competency

5.2.6 Difference in responses according to occupation

Kruskal-Wallis’s test was used to study the difference in responses according to occupation, the results shown in table (see table 7).

Table (7) shown Difference in responses according to occupation (n =113)

Variable	Occupation	N	Mean Rank	H	Sig.
Nature & Severity Impact of Phenomenon	Marine superintendent	11	57.45	5.13	0.40
	Ship master	27	59.22		
	Marine navigator	37	59.45		
	Marine instructor	6	30.67		
	Researcher	20	61.18		
	Other	12	50.25		
Effectiveness of Preparedness	Marine superintendent	11	52.09	3.93	0.56
	Ship master	27	57.56		
	Marine navigator	37	63.92		
	Marine instructor	6	50.42		
	Researcher	20	55.38		
	Other	12	44.92		
Human Capacity Building and Training Needed for Human Factor and Awareness	Marine superintendent	11	39.05	14.33	0.01
	Ship master	27	61.20		
	Marine navigator	37	65.00		
	Marine instructor	6	29.67		

Variable	Occupation	N	Mean Rank	H	Sig.
	Researcher	20	63.40		
	Other	12	42.33		
Alternative Navigation Means	Marine superintendent	11	54.05	8.24	0.14
	Ship master	27	67.17		
	Marine navigator	37	61.19		
	Marine instructor	6	39.67		
	Researcher	20	51.38		
	Other	12	41.96		
Regional & International Cooperation	Marine superintendent	11	39.32	15.08	0.01
	Ship master	27	59.74		
	Marine navigator	37	63.09		
	Marine instructor	6	43.50		
	Researcher	20	68.73		
	Other	12	35.46		

Figure (14) shows that differences in responses about the level of Human Capacity Building and Training Needed for Human Factor and Awareness, and Regional & International Cooperation according to occupation are significant at the level of significance (0.05). Mean of Marine navigator and Researcher responses was significantly higher, which can be interpreted Specifically as the marine navigators and researchers rated the need for these factors higher suggests that these groups perceive the importance of human capital development and international collaboration in addressing the challenges posed by geomagnetic reversals.

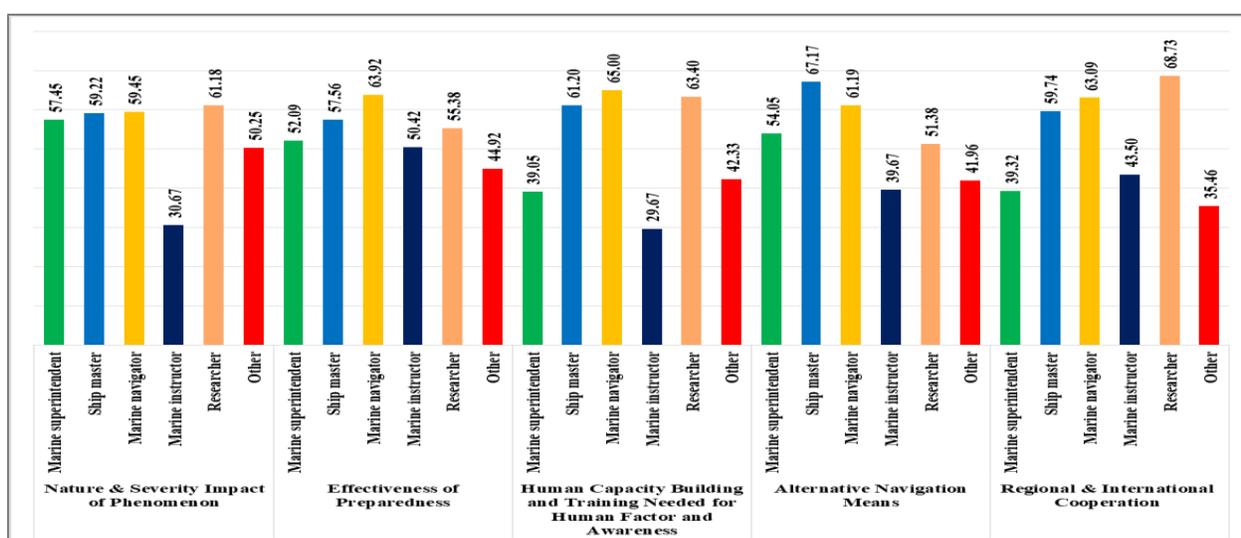


Figure (14) Results of responses according to occupation

5.2.7 Difference in responses according to years of experience

Kruskal-Wallis’s test was used to study the difference in responses according to years of experience, the results shown in table (see table 8).

Table (8) shown Difference in responses according to years of experience (n =113)

Variable	Years of Experience	N	Mean Rank	H	Sig.
Nature & Severity Impact of Phenomenon	< 7 years	33	54.42	0.32	0.96
	7-15 years	45	58.27		
	16-29 years	17	58.65		
	> 30 years	18	57.00		
Effectiveness of Preparedness	< 7 years	33	55.71	0.73	0.87
	7-15 years	45	58.41		
	16-29 years	17	52.12		
	> 30 years	18	60.44		
Human Capacity Building and Training Needed for Human Factor and Awareness	< 7 years	33	53.65	1.51	0.68
	7-15 years	45	55.32		
	16-29 years	17	61.50		
	> 30 years	18	63.08		
Alternative Navigation Means	< 7 years	33	52.61	2.09	0.55
	7-15 years	45	55.46		
	16-29 years	17	65.18		
	> 30 years	18	61.19		
Regional & International Cooperation	< 7 years	33	59.14	0.89	0.83
	7-15 years	45	53.92		
	16-29 years	17	56.85		
	> 30 years	18	60.92		

Figure (15) shows that differences in responses according to years of experience are insignificant at the level of significance (0.05).

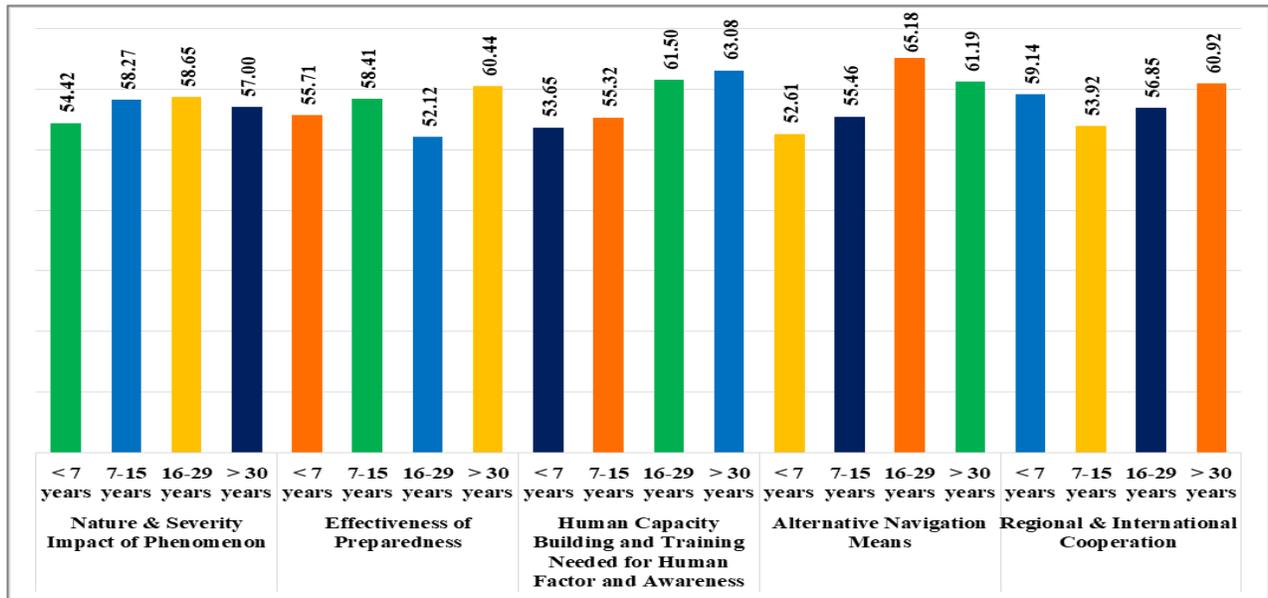


Figure (15) Results of responses according to years of experience

5.3 TEST THE STUDY'S HYPOTHESES

5.3.1 Nature & Severity Impact of Phenomenon

For Sub-Hypothesis 1: would A geomagnetic reversal would be a significant disruption.

The results in table (see table 9) shows Chi-Square test results show that differences in responses about all items of Nature & Severity Impact of Phenomenon are significant at the level of significance (0.01), Which can be interpreted as strongly agreed & accepted with the study point of view also This suggests that these factors are influencing perceptions and beliefs about the phenomenon; also achieved the research objectives “Investigate the nature and severity of geomagnetic reversals and their potential impacts on the maritime navigation.” & “Analyze the vulnerabilities of existing maritime navigation systems and techniques to geomagnetic reversals”.

Table (9) shown Results for Nature & Severity Impact of Phenomenon (n =113)

Item	Chi-square
A geomagnetic reversal would completely disable most of ship navigation systems	39.53**
Positioning and communication systems through satellites would experience significant disruptions during a reversal	82.27**
Current Modern marine navigation systems would experience significant disruptions during a reversal	63.18**
Geomagnetic storms can lead to disturbance in electric power	51.28**

Item	Chi-square
Geomagnetic polarity reversals have a significant impact on Earth's climate	59.78**
The maritime industry would experience significant economic losses due to navigation disruptions	62.61**

(** refer to sig at 0.01)

5.3.2 Effectiveness of preparedness

For Sub-Hypothesis 2: can Maritime navigation necessitates effective preparedness significantly reduce these disruptions.

The results in table (see table 10) shows Chi-Square test results show that differences in responses about all items of Effectiveness of Preparedness are significant at the level of significance (0.01), Which can be interpreted as accepted; also achieved the research objective “Evaluate the effectiveness of various preparedness strategies for mitigating the negative consequences of geomagnetic reversals on maritime navigation.”

Table (10) Shown Results for Effectiveness of Preparedness (n =113)

Item	Chi-square
1) Effective preparedness actions can significantly reduce the disruptions caused by a geomagnetic reversal on maritime navigation	82.53**
2) The current level of preparedness in the maritime industry is sufficient to handle the challenges of a geomagnetic reversal	15.01**
3) A deeper understanding of Earth's core dynamics, achieved through advanced study of fluid motion and the underlying physical processes,	75.54**
4) I am confident that current ship navigation systems can be adapted through modifications, or the adoption of newly methods to function effectively during a geomagnetic reversal	79.35**

(** refer to sig at 0.01)

5.3.3 Human capacity building

For Sub-Hypothesis 3: will investing in human capacity building comprehensive programs and familiarization of the nature of phenomena reduce the negative impact of the reversal on maritime industry.

The results in table (see table 11) shows Chi-Square test results show that differences in responses about all items of Human Capacity Building and Training Needed for Human Factor and Awareness are significant at the level of significance (0.01), Which can be interpreted as strong good sample respondents agreed with the study; also achieved the research objective “To Evaluate the effectiveness of various preparedness strategies for mitigating the negative consequences of geomagnetic reversals on maritime navigation”.

Table (11) Shown Results for Human Capacity Building and Training Needed for Human Factor and Awareness (n =113)

Item	Chi-square
• Investing in comprehensive human capacity building programs focused on geomagnetism, alternative navigation, and mitigation strategies is essential for managing the negative impact of reversals on the maritime industry	112.97**
• Extensive training on the nature of geomagnetic reversals and alternative navigation methods is crucial for mariners	114.57**
• In your opinion, is understanding of geomagnetic reversals and their potential impact for mariners is essential to navigate safely during such events	34.32**
• I believe mariners need to be familiar with methods to mitigate the impact of geomagnetic reversals on positioning systems	68.06**
• Regular drills and training sessions on navigating during geomagnetic polarity reversals are essential for strengthens maritime capacity	80.38**

(** refer to sig at 0.01)

5.3.4 Alternative navigation means & new technologies

For Sub-Hypothesis 4: Is the potential of alternative navigation systems ensure safe and reliable ship navigation during geomagnetic reversals.

The results in table (see table 12) shows Chi-Square test results show that differences in responses about all items of Alternative Navigation Means are significant at the level of significance (0.01), Which can be interpreted as accepted; also achieved the research objective “To Evaluate the effectiveness of various preparedness strategies for mitigating the negative consequences of geomagnetic reversals on maritime navigation”.

Table (12) Shown Results for Alternative Navigation Means (n =113)

Item	Chi-square
1. Existing and emerging alternative navigation systems have the potential to ensure safe and reliable ship navigation during a geomagnetic reversal	68.19**
2. Alternative navigation systems are unlikely to be effective substitutes for current GNSS systems during a reversal	56.42**
3. Traditional navigation techniques, such as celestial navigation, are not affected by geomagnetic reversals	90.05**

Item	Chi-square
4. The integration of advanced celestial navigation in modern techniques and automated data analysis systems would significantly improve the effectiveness of celestial navigation during a geomagnetic reversal	95.10**
5. do you believe that prioritizing the development and improvement of alternative navigation systems is essential for ensuring the continued viability of safe maritime navigation during a geomagnetic reversal polarity	104.65**

(** refer to sig at 0.01)

5.3.5 Regional & international cooperation

For Sub-Hypothesis 5: Is Encouraging global cooperation on research, data sharing, and standardized protocols complex due to varying political priorities and resource distribution; in addition of adaption of strong legal frame work.

The results in table (see table 13) shows Chi-Square test results show that differences in responses about all items of Regional & International Cooperation are significant at the level of significance (0.01), Which can be interpreted as strongly accepted; also achieved the research objective “To Evaluate the effectiveness of various preparedness strategies for mitigating the negative consequences of geomagnetic reversals on maritime navigation”

Table (13) Shown Results for Regional & International Cooperation (n =113)

Item	Chi-square
1. Encouraging global cooperation on research, data sharing, and standardized protocols for navigation during geomagnetic reversals is essential for effective preparedness	140.85**
2. The availability of regular, up-to-date information technology regarding navigation challenges during a geomagnetic reversal would be helpful for ensuring safe maritime operations	118.02**
3. In your opinion, would a strong international legal framework and treaties; specifically addressing geomagnetic reversals and their impact on navigation, would encourages safety of navigation during this event	83.28**

(** refer to sig at 0.01)

5.4 The Findings Determined Several Key Points

- **Limited Awareness:** A significant portion of the maritime industry demonstrates limited awareness of the potential risks and implications of geomagnetic reversals.
- **Inadequate Preparedness:** The current level of preparedness within the industry is insufficient to effectively address the challenges posed by geomagnetic disruptions.

- **Critical Role of Human Capacity Building:** Investing in training and education is crucial for equipping maritime professionals with the skills needed to navigate during these events. There is strong support for comprehensive training programs covering geomagnetism, alternative navigation, and mitigation strategies.
- **Potential of Alternative Navigation Systems:** While current navigation systems are considered vulnerable, participants believe that alternative technologies, particularly those integrating advanced celestial navigation with modern systems, offer potential mitigation strategies. Further development and refinement of these alternatives are deemed essential.
- **Importance of International Cooperation:** Collaborative efforts between nations, including research sharing, standardized protocols, and legal frameworks, are considered crucial for a coordinated and effective response to geomagnetic reversals.

6- Conclusion

This paper explored the complex relationship between Earth's dynamic magnetic field and maritime safety of navigation, examining the potential impacts of the expected geomagnetic reversals and the necessary preparedness measures. The paper discussed the foundational understanding of the Earth's magnetic field, its dynamic nature, and the phenomenon of geomagnetic reversals, including their potential consequences for technological systems, particularly in maritime navigation. Also, it focused on the practical implications for navigation, examining how geomagnetic phenomena can disrupt compasses, electronic navigation systems, and modern maritime practices.

The research findings underscore that while the possibility of a geomagnetic reversal is a long-term prospect, the dynamic nature of the Earth's magnetic field necessitates proactive preparation. Ensuring the resilience of navigation systems in the face of a potentially weakened or reversed magnetic field requires a multifaceted approach encompassing technological advancements, human preparedness, and international collaboration.

The paper recommended several potential solutions for emergency backup navigation, including inertial navigation systems, star trackers, handheld celestial navigation systems, and celestial navigation plugins for ECDIS. These options warrant further exploration and development to ensure their effectiveness and practicality in a geomagnetic reversal scenario.

While the weakening of the Earth's magnetic field is a concern, it is important to emphasize that a full reversal is a process that could take decades or more. The effects are likely to be gradual, allowing time for adaptation and implementation of the strategies. Therefore, understanding the potential impact of geomagnetic reversals is not a cause for alarm but a call for proactive preparation. By embracing technological advancements, fostering skilled navigators, and establishing robust international collaboration, the maritime industry can ensure continued safe and efficient navigation, even during periods of geomagnetic instability.

6.1 Recommendations

1. Prioritizing Navigation Systems “Develop and test navigation systems with minimal reliance on the magnetic field”
2. Improve magnetometer technology for enhanced accuracy during weakened fields
3. Advance Inertial Navigation System (INS) technology
4. Develop user-friendly celestial navigation tools and apps
5. Enhance collaboration with space weather forecasting
6. Encouraging human capacity building
7. Address Public Awareness
8. Promote International Collaboration

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Assessment of onshore power supply for ship's emissions reduction in Alexandria Port utilizing national grid/ renewable energy

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المستخلص

تُعد مشكلة تلوث الهواء الناتجة عن الشحن البحري قضية هامة، خاصة في المدن الساحلية. من بين الحلول المقترحة، نظام تزويد الطاقة من الشاطئ (OPS)، حيث تقوم السفن بفصل محركاتها الاحتياطية والتواصل مع شبكة الكهرباء في الميناء. رغم الدراسات المتعددة في موانئ أوروبا والولايات المتحدة، تركز هذه الدراسة على تطبيق نظام OPS في ميناء الإسكندرية بما يتماشى مع رؤية مصر 2030 في مواجهة تغير المناخ.

تركز الدراسة على تحليل البيانات المجمعة من السفن لتقديم تحليل اقتصادي وتقييم الانبعاثات الناتجة عن استخدام النظام. كما تستعرض استخدام الطاقة الشمسية كمصدر للكهرباء لتحسين الفعالية البيئية للنظام. تشير النتائج إلى أن الاعتماد على الشبكة الوطنية يقلل الانبعاثات بنسبة تصل إلى 27.5%، بينما يمكن للطاقة الشمسية تقليل الانبعاثات بنسبة تصل إلى 100%.

تنفيذ نظام OPS المعتمد على الطاقة الشمسية في ميناء الإسكندرية لا يساهم فقط في تحسين جودة الهواء، بل يعزز أيضاً الأهداف البيئية والاجتماعية والاقتصادية للبلاد، ويسهم في تحسين جودة الحياة والتنمية المستدامة.

ABSTRACT

Air pollution from shipping is a critical issue, especially in dense ports. One of the proposed technologies to reduce ship emissions in ports is the Onshore Power Supply (OPS) system, where ships turn off their auxiliary electric generator engines and connect into the port grid. Several studies were conducted in European and USA ports. This study tackles the application of the OPS in the port of Alexandria, in line with Egypt's Vision 2030 concerning the issue of climate change. The study focuses on analyzing the ships data collected from Alexandria port along one month. The present investigation aiming to conduct a comprehensive socio-economic and cost effectiveness analyses of OPS. To enhance the environmental potential of OPS, deploying four solar energy scenarios as the OPS electricity source is proposed.

The results revealed that relying on the national grid decreases emissions by 27.5%, and it is predicted to reach 100% if the electricity is generated from solar energy. Also, the economic analysis shows good profitability with a payback period of almost two years. Therefore, the implementation of the solar-powered OPS system in Alexandria port not only contributes to improving the air quality in the area, but also enhancing the country's environmental, social and

economic goals. Improving port infrastructure and using clean energy technologies can significantly enhance the quality of life in port cities and promote sustainable development.

Keywords: Onshore Power Supply, Renewable Energy, Solar Energy, Alexandria Port, Ship Emissions, Sustainable Development.

1- Introduction

Maritime transport facilitates global trade efficiently but relies heavily on fossil fuels, contributing approximately 2.89% of global CO₂ emissions in 2018—a figure projected to rise by 50% by 2050 without intervention (IMO, 2021). Notably, 70% of emissions occur within 400 km of land, heavily affecting ports (Corbett et al., 2007), where ship emissions can contribute up to 54% of total port emissions (Merk, 2014). Such emissions pose health risks, while noise pollution from auxiliary generators exacerbates cardiovascular and hearing issues (Badino et al., 2012).

The IMO has adopted measures such as the Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP) since 2013, alongside sulfur and nitrogen emissions limits and noise regulations (IMO, 2020). Onshore Power Supply (OPS) systems offer a viable solution by enabling ships to connect to port grids, eliminating emissions, noise, and vibration from auxiliary engines during berthing (Zis, 2019). When integrated with renewable energy sources (RES) like solar or wind, OPS amplifies environmental benefits (Yarova et al., 2017). However, OPS requires substantial investment, necessitating cost-benefit analyses and prioritization for high-traffic, densely populated ports (Zis, 2019).

In Egypt, Alexandria Port serves as a key Mediterranean hub. While Damietta Port pioneered OPS in 2019, Alexandria Port also has shore power-ready berths (Mohamed & Salah-Eldine, 2020). Limited research explores OPS adoption in Egyptian ports, particularly with RES integration. This study investigates OPS implementation in Alexandria Port, emphasizing solar energy as a power source, aligning with Egypt's Vision 2030 to enhance socio-economic and environmental sustainability.

2- Literature Review

The implementation of (OPS), or shore-side electricity (SSE), is a key solution to reducing emissions from ships at berth. By connecting to shore power, ships can shut down diesel engines, eliminating emissions of CO₂, SO_x, and NO_x during docked operations (Dai, et al., 2020). This aligns with regulations from the EU Commission and IMO, aiming to lower shipping emissions in sensitive coastal areas (Kumar, et al., 2019). OPS significantly improves air quality and reduces noise pollution, benefiting port cities and nearby residential areas (Martínez-López, et al., 2021). Ports in California, Europe, and China have adopted OPS to comply with strict environmental laws, achieving substantial CO₂ reductions, such as 99.5% in Oslo and 85% in France (Dai et al., 2019; Kotricla, et al., 2017). These benefits are especially critical in high-traffic ports like Shanghai, where air pollution poses severe health risks (Radwan et al., 2019). Infrastructure for OPS includes shore power sources, transformers, and communication systems, ensuring safe and

efficient electricity transfer to ships. While complex to implement, OPS aligns with global environmental goals, such as the IMO’s MARPOL Annex VI and the EU Green Deal, which require ports to meet 90% of ships' energy needs via shore power by 2025 (Wu and Wang, 2020). By reducing fuel consumption, emissions, and noise pollution, OPS supports sustainability and compliance with international regulations. As more ports adopt this technology, it plays a pivotal role in transitioning the maritime industry toward greener practices (Winkel et al., 2016). The ship’s electrical power load is shifted to an on-shore power supply source of electrical power without disruption to onboard services, as shown in Figure (1).

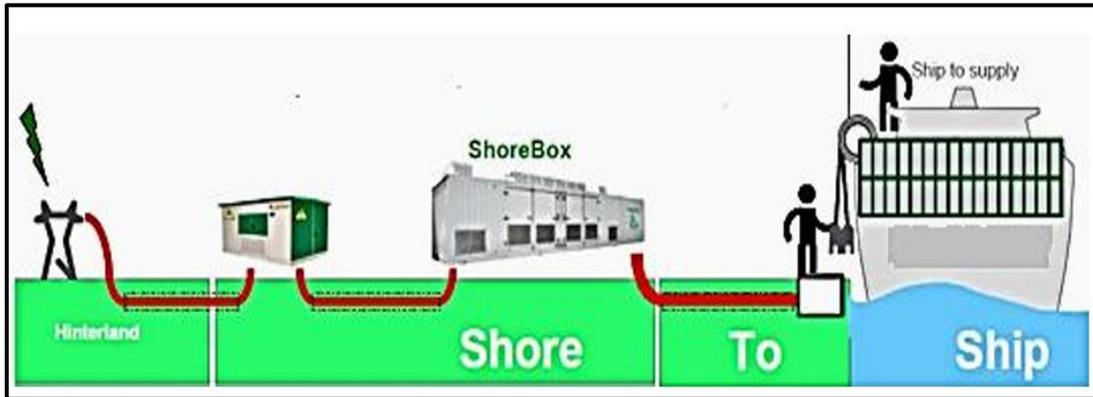


Figure (1) OPS configuration [Baltic Ports Organization (2015)]

3- Case Study: Alexandria Port

The Port of Alexandria is Egypt's largest and most important port, handling about 60% of the country's foreign trade. Located on the Mediterranean coast at the western edge of the Nile Delta, it connects Egypt with Europe, Asia, and Africa. The port has two main areas: the shallow Eastern Port and the deeper Western Port, which handles most cargo and passenger traffic. Covering 8.4 km² (6.8 km² water, 1.6 km² land), it has 55 berths with a maximum draft of 16 meters, accommodating various vessel types (Alexandria Port.2024). Its strategic location makes it a key player in Egypt's global maritime trade, especially with Europe.



Figure (2) Map of Alexandria Port (Alexandria Port, 2024).

The port serves a wide range of commercial, industrial, and logistical functions, with basins designed for different types of vessels. The port has multiple quays, storage facilities, grain silos, and a logistics zone, all connected to Egypt’s road and rail networks for efficient cargo movement. The port located near the Suez Canal, and handles 60-70% of Egypt’s foreign trade, making it a cornerstone of the national economy. Figure (2) present Alexandria port map showing its layout, highlighting key areas such as basins for different vessels, quays for loading and unloading, storage zones, and its access to major transportation routes, underlining its crucial role in global and domestic trade.

4- Methodology

The research adopts an analytical and comparative approach to establish an environmental framework for applying green port operating principles. The methodology involves three main axes: data collection from Alexandria Port’s operating systems and ship activities, analyzing energy consumption scenarios during various operational states, and using software to calculate emissions and carbon footprints from ship generators.

The study focuses on ocean-going vessels due to limited data availability, with ships classified by function and cargo type. Data provided by the Alexandria Port Authority includes ship specifications, arrival, and departure times. The research compares the environmental and economic impacts of traditional ship generators versus an OPS system in the port.

4.1 Ship emissions inventory

4.1.1 EPA method

EPA methodology for estimating total emissions from auxiliary engines onboard ships during specific operations is detailed by EPA (2017). Equation (1) is utilized to calculate the emissions (E_i) of specific pollutants from auxiliary engines during the hoteling phase.

$$E_i = P_j * LF_j * C_j * T_j * EFi \quad (1)$$

Where, P_j represents the total auxiliary engine power demand in port, LF_j is the hoteling load factor, C_j denotes the number of ship port calls, and T_j is the hoteling time.

The emission factors (EF_i) for Marine Diesel Oil (MDO) with 0.5% sulfur content used in auxiliary engines are provided in Table (1) (EPA 2017),

Table (1) Emissions factors of MDO (g/kWh) [EPA 2017].

Fuel Type	CO ₂	So _x	NO _x		PM ₁₀	PM _{2.5}
			Tier 0	Tier 2		
MDO (0.5%S)	690	2.1	13.9	9.7	0.38	0.35

In this study, NO_x emissions are calculated based on Tier 0 and Tier II standards, depending on the ship's age and rated engine speed. Tier 0 standards apply to ships built before 2000, while Tier

II standards apply to ships built after 2000. Even if a ship's construction date allows it to operate under Tier I standards, it is assumed to comply with Tier II standards, as per Chapter 5 of the Emissions Inventory Methodology (Faried 2024). Tier III standards, applicable only in NOx emission control areas, are excluded from the study.

4.1.2 IMO method

The International Maritime Organization (IMO) has set regulations to calculate greenhouse gas (GHG) emissions from ships, including exhaust emissions in ports. The methodology uses various equations to estimate CO₂ and other pollutants based on available data accuracy. IMO guidelines help coastal states and local authorities create policies to reduce GHG emissions from ships in their ports (IMO, 2023). To estimate emissions from ship auxiliary engines (E_i), the auxiliary engine Fuel Consumption (FC_i) is first calculated (equation 2), followed by emission calculation using equation (3).

$$FC_i = SFC_{base} * WAE \quad \text{g/kWh} \quad (2)$$

$$E_i = FC_i * EF_f \quad \text{g/kWh} \quad (3)$$

Where, WAE represents the auxiliary engines' power output, and the Baseline Specific Fuel Consumption (SFC_{base}) is the lowest specific fuel consumption observed in their loading curve. The (SFC_{base}) of an auxiliary engine can be determined based on its year of construction, as shown in Table (2), (IMO, 2020).

WAE is the Weighted Average Efficiency and it consider as a factor that accounts for the vessel's performance under various operational conditions, such as speeds, loads, and other parameters

Table (2) SFC_{base} (g/kWh) based on engine age and fuel type (IMO, 2020)

Engine Type	Fuel Type	Before 1983	1984- 2000	2001+
Auxiliary Engines	MDO	210	190	185

4.2 Ship Information Application

The database used in this study includes data on over 300,000 commercial ships, covering ship specifications, equipment, and communication systems. It provides information on each ship's power generation capacity in kilowatts. Additionally, port data such as berthing days, working hours, and generator load factor were used to calculate the ship's total energy consumption in Gigawatt-hours (GWh) per port call. Emission factors for auxiliary engines during various ship operations depend on the fuel type used. Data from Alexandria port in October 2019 was used to estimate energy consumption during berthing. Equation (4) was used to calculate CO₂ emissions generated by ships in the port (Yahya, 2022; Joseph, Patil, and Gupta, 2009).

$$E = P \times LF \times EF \times T \quad (4)$$

Where.

E: emissions in units of pollutant

P: maximum power output of the auxiliary engine in kW presented from ship data.

LF: load factor for auxiliary engines, as a fraction of maximum, installed power capacity (40% of ship total Aux. Engine Capacity).

EF: emission factor (pollutant specific) in mass emitted per work output (in kWh) of the auxiliary engine in maneuvering and berthing modes, g/kWh,

T: maneuverings and berthing time in hours.

4.3 Ship emission in the study period

Emission calculations for ships at Alexandria port during the study period (1/10/2019 to 31/10/2019) showed significant variation based on ship type and number. Bulk carriers were the largest contributors, accounting for 52.19% of total emissions. Container ships followed with 20.13%, while other ship types, such as general cargo vessels (11.85%) and oil tankers (6.49%), contributed lower percentages. Figure (3) illustrates the emission percentages of various ship types during the study period.

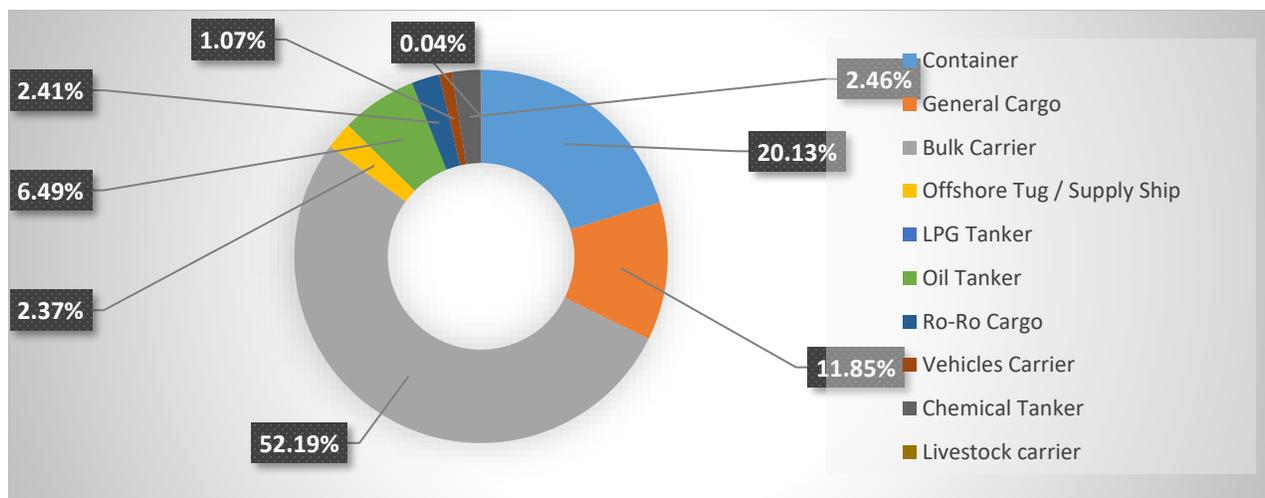


Figure (3) Percentage Breakdown of CO₂ Emissions by Ship Type

4.4 Assessment of solar energy resource

Solar technology is widely used due to its reliability, flexibility, and longevity. Alexandria, Egypt, located within a high solar irradiation region (1980.9 kWh/m² direct normal irradiation), is ideal for solar energy generation as seen in figure (4). Utilizing renewable sources like solar energy addresses climate change, fossil fuel depletion, and energy security concerns, aligning with the Paris Agreement's goals for reducing greenhouse gas emissions. Rooftop spaces, like warehouse roofs in port areas, can be effectively used for solar energy generation. Photovoltaic (PV) technology is growing due to decreasing costs and increasing efficiency. Marine solar energy is a promising new option, offering higher power production (5-10% more) and minimizing land use compared to land-based projects.

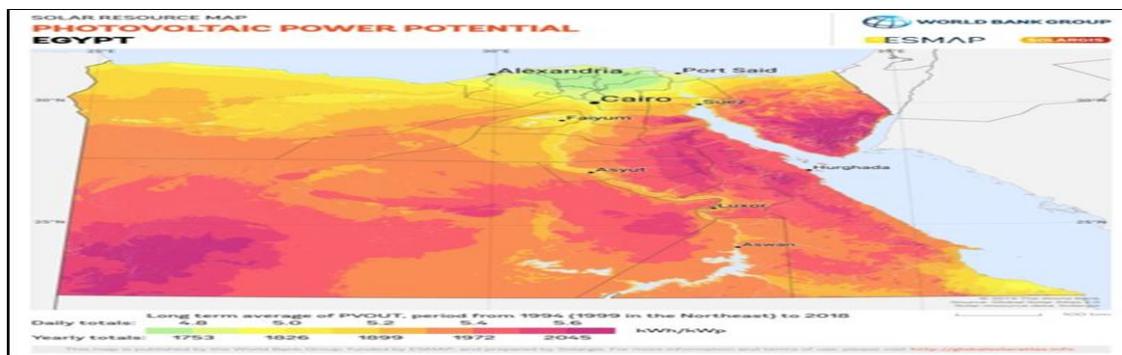


Figure (4) Map of average annual solar irradiation in Egypt (SolarGIS, 2018)

Egypt's geographical location between latitudes 22° and 31° north places it in the subtropical region, making it one of the most sun-exposed countries year-round. Solar radiation in Egypt ranges from 5-6 kWh per square meter per day, particularly in desert areas. The heat map shows temperature variations, with moderate coastal temperatures and higher temperatures in the desert during summer. This location offers a great opportunity to harness solar energy for electricity generation, supporting renewable energy projects and contributing to reduced emissions and environmental sustainability.

4.4.1 Proposal of OPS system in Alexandria port

In order to improve the environmental performance of the proposed OPS system at Alexandria Port, the OPS should provide berthed ships with electricity from a clean source such as solar energy. Therefore, a sensitivity analysis of the available unused open area and deck areas of buildings and warehouse ceilings located within the port is carried out to assess the potential for installing a photovoltaic system. Table (3) presents the five scenarios proposed for selected areas to install the PV system, which covers the four scenarios regarding the available area inside Alexandria Port as follows;

Table (3) Impact of Energy Scenarios on Solar Generation and Emissions Reduction

Scenario	Main power source	Total Solar Energy Generated (kW)	Energy Savings Achieved (%)	Remaining Energy After Solar (kW)	Calculated Emission Reduction by percentage
First scenario	Natural gas	0	0%	47083	27.5%
Second Scenario	25% of solar and natural gas use	11306.75	24%	35776.25	44.93%
Third Scenario	50% solar and natural gas use	22613.5	48%	24469.5	62.34%
Fourth scenario	75% solar and natural gas use	33920.25	72	13162.75	89.3%

Fifth scenario	100% solar and natural gas use	45227	96%	1866.5	97.12%
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Figure (5) presents the impact of five energy scenarios on solar energy generation and emissions reduction. In the first scenario, which relies entirely on natural gas, no solar energy is generated, resulting in no energy savings but a 27.5% reduction in emissions. In the second scenario, 25% of solar energy is combined with natural gas, generating 11,306.75 kW of solar power, resulting in a 24% energy savings and a 44.93% emissions reduction. With a 50% solar share in the third scenario, solar energy generation increases to 22,613.5 kW, achieving a 48% energy saving and a 62.34% emissions reduction. In the fourth scenario, where 75% solar and 25% natural gas are used, 33,920.25 kW of solar power is generated, resulting in a 72% energy savings and an 89.3% reduction in emissions. Finally, in the fifth scenario, which relies entirely on solar energy, 45,227 kW of solar energy is generated, achieving a 96% energy saving and a 97.12% emissions reduction. These results demonstrate the significant benefits of transitioning to solar energy, not only in terms of energy savings but also in reducing harmful emissions, thus enhancing the role of renewable energy in achieving environmental sustainability.

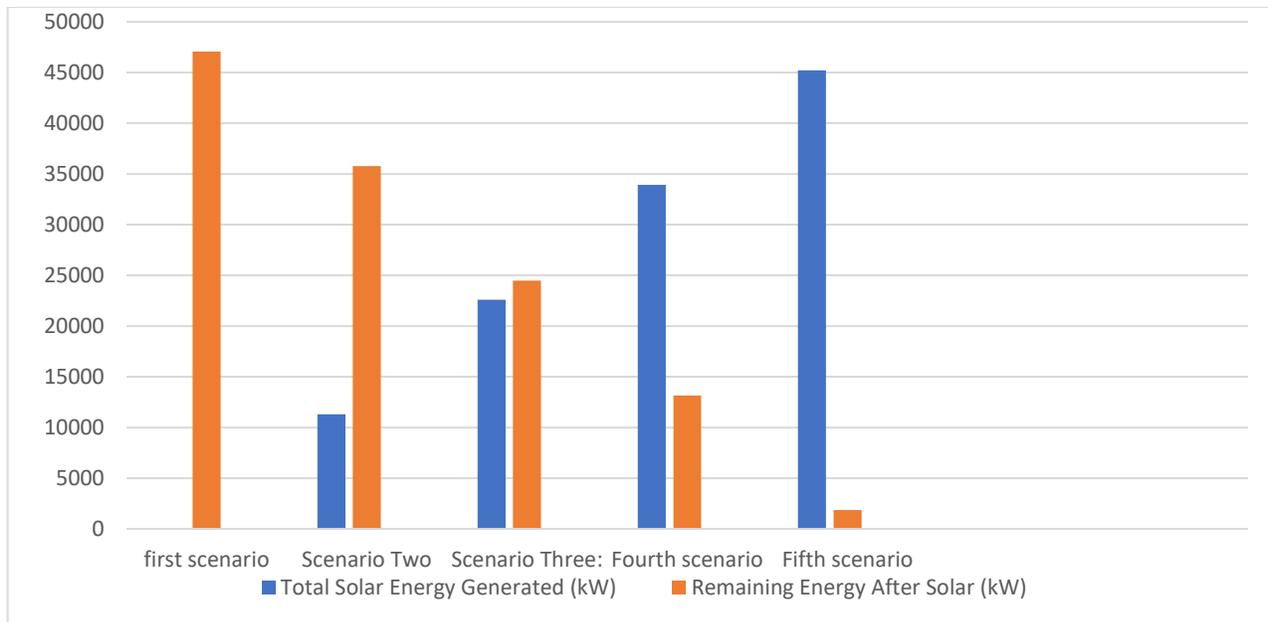


Figure (5) The Impact of Increasing Solar Energy Utilization on Reducing Energy Consumption and Emissions

5- Results and Discussion

5.1. Statistical Analysis

Table (4) represents the percentage of container ships, general cargo ships, and other types that entered the Port of Alexandria, with classification and detailing of all information such as the period, the number of ships for each type, and the amount of energy consumption.

Table (4) Results of data of ships entering the port

Ship type	Number of ships	Period	Total co2 ton	Percentage of pollution	amount of energy consumed per type kWh
Container	108	01/10/2019 to 31/10/2019	8540.388	% 20.13	229635
General Cargo	90		5026.734	% 11.852	49478
Bulk Carrier	62		22136.404	% 52.19	82977
Offshore Tug / Supply Ship	22		1008.416	% 2.37	36364
LPG Tanker	8		410.222	%0 .967	4487
Oil Tanker	27		2752.814	% 6.490	32912
Ro-Ro Cargo	16		1022.586	% 2.411	43621
Vehicles Carrier	9		454.552	% 1.07	26787
Chemical Tanker	13		1043.114	% 2.459	14445
Livestock carrier	1		15.8976	% 0.037	600

Analysis of vessel data for Alexandria Port from 1 to 31 October 2019 reveals significant differences in emissions and energy consumption among ship types. Bulk carriers (62 ships) were the largest contributors, producing 52.19% of CO2 emissions (22,136 tonnes) and consuming 82,977 kWh. Container ships (108 ships), while contributing only 20.13% of emissions (8,540 tonnes), had the highest energy consumption at 229,635 kWh, reflecting their greater energy demands.

General cargo ships and oil tankers had moderate impacts, contributing 11.85% and 6.49% of emissions, respectively, with energy consumption of 49,478 kWh and 32,912 kWh. Smaller vessels like LPG carriers and livestock carriers had minimal emissions and energy usage.

These results, specific to October 2019, emphasize that impacts vary by ship type and time period, highlighting the need for tailored strategies to enhance efficiency and reduce environmental effects. Figure (6) depicts the average electricity consumption for each ship category during the study.

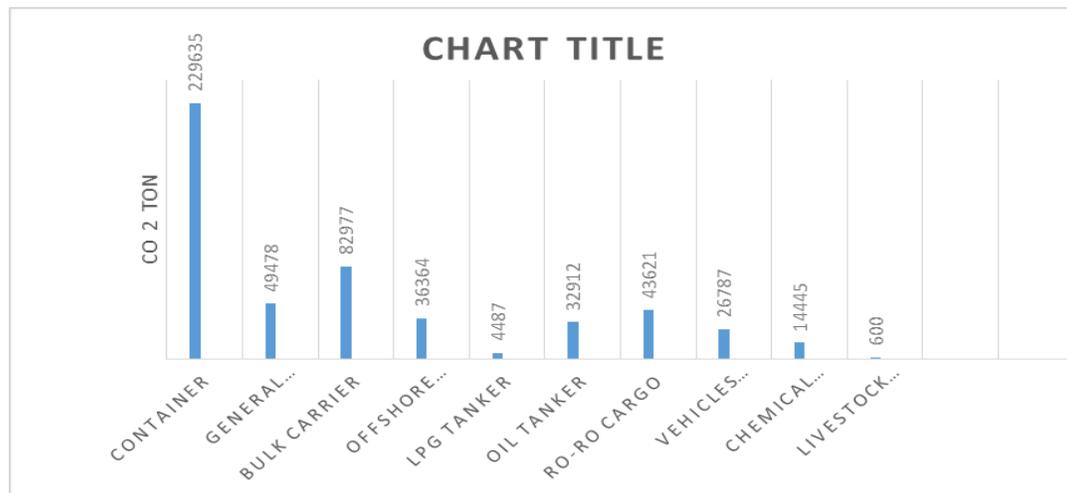


Figure (6) CO₂ Emission Rate by Ship Type

5.2. Socio-Economic Analysis

The analysis examines the cost of CO₂ emissions from ships in ports, comparing damages with and without an (OPS) system. At \$50 per ton (Ferried, 2024), emissions during the study period using onboard diesel generators cost \$2,115,556.38. Implementing OPS, powered by the national grid, reduces emissions damage costs by 27.5%, saving \$581,677.90 and lowering costs to \$1,533,878.48.

OPS enhances air quality, reducing health risks like respiratory and cardiovascular diseases, and aligns with sustainability goals. Integrating renewable energy, such as solar power, into OPS cuts long-term operating costs despite high initial investment. This transition boosts energy efficiency, reduces fossil fuel dependence, and ensures sustainable port operations.

5.3. Assessment of Solar Energy Resource

To enhance the environmental performance of the proposed solar power plant project, it is essential to integrate renewable energy sources into the national grid. This approach allows the solar power plant to provide clean electricity to moored vessels, significantly reducing emissions. A sensitivity analysis was conducted to explore available spaces within the port for solar panel installation, leading to several scenarios:

1. **First Proposal:** By utilizing vacant yards and rooftops of port buildings at 25% capacity, solar panels can meet approximately 24% of the electrical energy needs of moored vessels, with the remainder supplied by the national grid.
2. **Second Proposal:** By incorporating some rooftops of warehouses and administrative offices at 50% capacity, solar panels can provide 48% of the required electricity.
3. **Third Proposal:** Using both vacant yards and rooftops of warehouses and offices at 75% capacity, solar installations can cover 72% of the energy needs.
4. **Fourth Proposal:** Maximizing the use of all available spaces can enable solar power to cover up to 96% of electricity needs.

The total energy consumption is approximately 47,083 kilowatt-hours, while the generated solar energy can reach around 45,227 kilowatt-hours with full installation. This high coverage rate is

particularly beneficial during the summer months but may decrease in winter due to increased electricity demand, highlighting the necessity for an energy storage system to manage peak demand.

5.4. Cost-Effectiveness Analysis

A Net Present Value (NPV) analysis was conducted to assess the feasibility of Onshore Power Supply (OPS) systems, where positive NPVs indicate viability. OPS becomes profitable when savings in electricity and external costs exceed total private costs. The analysis considered the transition from the national grid to solar energy at Alexandria Port, which has a peak daily electricity consumption of 47.8 MW, costing approximately \$4,971.20 at a fossil fuel rate of \$104/MW.

Integrating solar energy for 25%, 50%, 75%, and 100% of the port's electricity needs results in cost reductions of 18.66%, 37.5%, 56.32%, and 75.05%, respectively. These findings demonstrate significant financial savings and reduced environmental impact with higher solar energy integration.

Table (5) illustrates the cost reductions based on different levels of solar energy integration.

Solar Energy Integration (%)	Cost Reduction (%)
25%	18.66%
50%	37.5%
75%	56.32%
100%	75.05%

5.5. Challenges Facing OPS Application in Egypt

The main challenges for implementing Onshore Power Supply (OPS) in Egypt, particularly at Alexandria Port, are:

- **Lack of Strong Regulations:** The absence of clear legislation hinders OPS adoption, unlike the US with strong regulations driving success.
- **Insufficient Compatible Vessels:** Ports hesitate to invest in OPS without enough compatible vessels, making it a high-risk investment.
- **Limited Applicability:** OPS is most effective for frequent transport services involving container ships, cruise ships, bulk carriers, and chemical tankers.

To effectively implement OPS at Alexandria Port, the following solutions should be considered:

- **Establish Regulations and Collaboration:** Strong regulations and cooperation among stakeholders are essential.
- **Financial Incentives:** Provide financial support, tax reductions, and port fee adjustments to encourage OPS integration.
- **Port Concessions:** Offer preferential docking and concessions for OPS-equipped vessels.
- **Incentivize Early Adoption:** Implement programs to reward early OPS adopters.
- **Awareness Campaign:** Promote OPS benefits, focusing on reduced emissions, fuel savings, and regulatory compliance.

6- Conclusion and Recommendations

Ships are a major contributor to global marine pollution, both in ports and coastal areas. Therefore, it's crucial to properly implement the (OPS) system to reduce emissions from ships. The study at Alexandria Port showed that emissions from auxiliary ship engines amounted to 42,311.13 tons in one month. Using the national grid for OPS reduced emissions by 27.5%, amounting to 30,677.57 tons. This reduction could be higher if solar energy were used. Using solar energy for OPS would significantly reduce emissions, especially if 100% of the port area is covered with solar panels. Additionally, the cost of damage from emissions is reduced by 27.5% compared to auxiliary engine emissions, and this would increase with clean energy sources. A Net Present Value (NPV) analysis showed that the most profitable scenario is using 100% of the available area with solar energy.

This study's methodology can serve as a foundation for similar research in other Egyptian coastal areas. To implement OPS at Alexandria Port, the following professional recommendations are proposed based on the analysis:

- Enhancing Regulatory Frameworks and Environmental Laws
- Encouraging Vessel Modification for OPS Compatibility:
- Investing in Port Infrastructure:
- Improving the Port's Energy Mix:
- Coordinating with Stakeholders and Offering Financial Incentives:
- Conducting Economic Feasibility Studies:
- Promoting Innovation and Sustainable Development:
- Raising Environmental and Health Awareness:

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Maritime Port Evolution: Balancing Operational Excellence with Zero-Emission Requirements in the Context of IMO 2050 Objectives

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المستخلص

تستكشف هذه الدراسة تطور الموانئ البحرية نحو تحقيق أهداف المنظمة البحرية الدولية (IMO) للوصول إلى انبعاثات صفرية بحلول عام 2050 مع الحفاظ على الكفاءة التشغيلية. كما تعتمد الدراسة على منهجية مختلطة تشمل تحليل دراسات حالة لموانئ عالمية رائدة مثل روتردام وسنغافورة ولوس أنجلوس ودبي وشرق بورسعيد. وتقيم الدراسة استخدام أنظمة الرقابة المتطورة والتقنيات الرقمية التي أظهرت تحسينات جوهرية في الأداء البيئي والكفاءة التشغيلية. كما تشير النتائج إلى أن الموانئ المزودة بأنظمة إدارة بيئية متكاملة حققت دقة بنسبة 98% في رصد الانبعاثات، وإنخفاضًا بنسبة 60% في وقت التوقف التشغيلي باستخدام تقنية إنترنت الأشياء (IoT). ومن ناحية أخرى تُبرز الدراسة عوامل النجاح الرئيسية مثل التكامل التكنولوجي، والتحالفات الإستراتيجية، وآليات التمويل المبتكرة وتقدم هذه الدراسة إطارًا نظريًا ومنهجيًا عمليًا لتعزيز القدرة التنافسية للموانئ في النظام البحري العالمي، مع التأكيد على ضرورة الإلتزام بالمعايير البيئية.

الكلمات المفتاحية: الموانئ البحرية، الأداء البيئي، الكفاءة التشغيلية، القدرة التنافسية للموانئ، التكامل التكنولوجي.

Abstract:

This study looks at how maritime ports have evolved toward the IMO's 2050 zero-emission goals while keeping operational excellence in mind. Additionally, the study uses a mixed methodology by examining case studies of prominent global ports like Rotterdam, Singapore, Los Angeles, Dubai, and East Port Said. The study also assesses the use of sophisticated monitoring systems and digital technologies, which have shown substantial improvements in both environmental performance and operational efficiency. In addition, the data suggests that ports with full-system environmental management systems resulted in emissions being monitored at 98% accuracy and a 60% reduction in operational downtime when IoT was used. Thereafter, the study highlights key success factors such as technological integration, strategic alliances, and innovative funding mechanisms. This study brings theoretical meaning and a practical approach to represent port competitiveness in the global maritime system, as ports must comply with the environment.

Keywords: Maritime ports, Environmental performance, Operational efficiency, Port competitiveness, Technological integration.

1- Introduction:

The Changing paradigms of port management for environmental challenges in the context of the rapid transformation of maritime transportation with the maritime sector responsible for a substantial share of global greenhouse gas emissions, the International Maritime Organization (IMO) has enshrined ambitious zero-emission targets by 2050 (Koilo, 2024). This imperative transforms into an unparalleled challenge for port authorities around the globe, as they deliver innovative solutions and strategic adjustment (Durlík et al., 2024). Sustainable port management has become the focus of maritime development, fueled by the advancement of sixth-generation ports and the fourth industrial revolution (Yau et al., 2020). The role of emerging advanced technologies such as digital technologies, alternative fuels, and smart infrastructure transforms challenges into opportunities and imposes complexity to sustain environmental compliance in parallel with targeting competitive advantage. As digital technologies, alternative fuels, and smart infrastructure converge, achieving environmental compliance and retaining competitive advantage will provide challenges and opportunities (Bougioukou, 2023).

The research tackles these key components of port decarbonization through the framework of three dominant dimensions:

- Strategic Implementation: The maritime sector finds itself under significant pressure to curb emissions whilst remaining operationally viable. Zero-emission vessel technologies, infrastructure modernization, and alternative fuel solutions require significant planning and resources (Ibokette et al., 2024).
- Technological Integration: Advanced technologies such as artificial intelligence, blockchain, and the Internet of Things (IoT) emerge as key drivers for environmental observation and compliance verification. All of these technologies enable real-time monitoring of emissions, optimization of energy efficiency, and compliance with regulations (Bashir, 2022).
- Regulatory Framework: The research explores the dynamic nexus among IMO regulations, regional regulations, and local environmental policies. Such a multi-level regulatory framework requires a holistic approach to strike the right balance of compliance and port competitiveness (Akac et al., 2023).

This research is important and contributes to the scientific body as it not only proposes frameworks for sustainable port management but also addresses the problem and the current challenges of implementing zero-emission implementation in current maritime activities (C. et al., 2024).

2- Literature Review:

The literature review conducts an organized review of the New Generation of port management complexities through a series of tightly connected themes and that the new generation of ports uses advanced environmental management systems together with their operational efficiency needs and the new green port initiatives transformed conventional port operations by introducing innovative techniques for environmental protection alongside emissions reduction strategies also the new generation of ports runs complex environmental management systems that allow successful

operations to be paired with environmental protection policies and the port operations have evolved with these new green initiatives providing innovative solutions to reduce emissions and preserve the environment (Cavalli et al., 2021) and also European ports demonstrate smart port technologies smoothly integrating renewable energy systems and alternative fuel infrastructure according to recent studies (Issa Zadeh et al., 2023).

Furthermore, Digital Transformation as a Foundational Operating Principle for Measuring Environmental Impacts coupled with advanced sensor networks offers precise recovery methodologies that can successfully assess emissions on top of the atmospheric variables (Su et al., 2024). The IMO's zero-emission targets require a significant transformation in the ecosystems of port infrastructures and operational practices (T. T. Le et al., 2023). Also, the growth of zero-emission tech is reliant on ports developing alternative fuel infrastructure (Govindan et al., 2024).

Figure (1): Temporal Evolution of IMO's Regulatory Framework for Maritime Greenhouse gases GHG Emissions Reduction: A Strategic Roadmap from 2011 to 2050

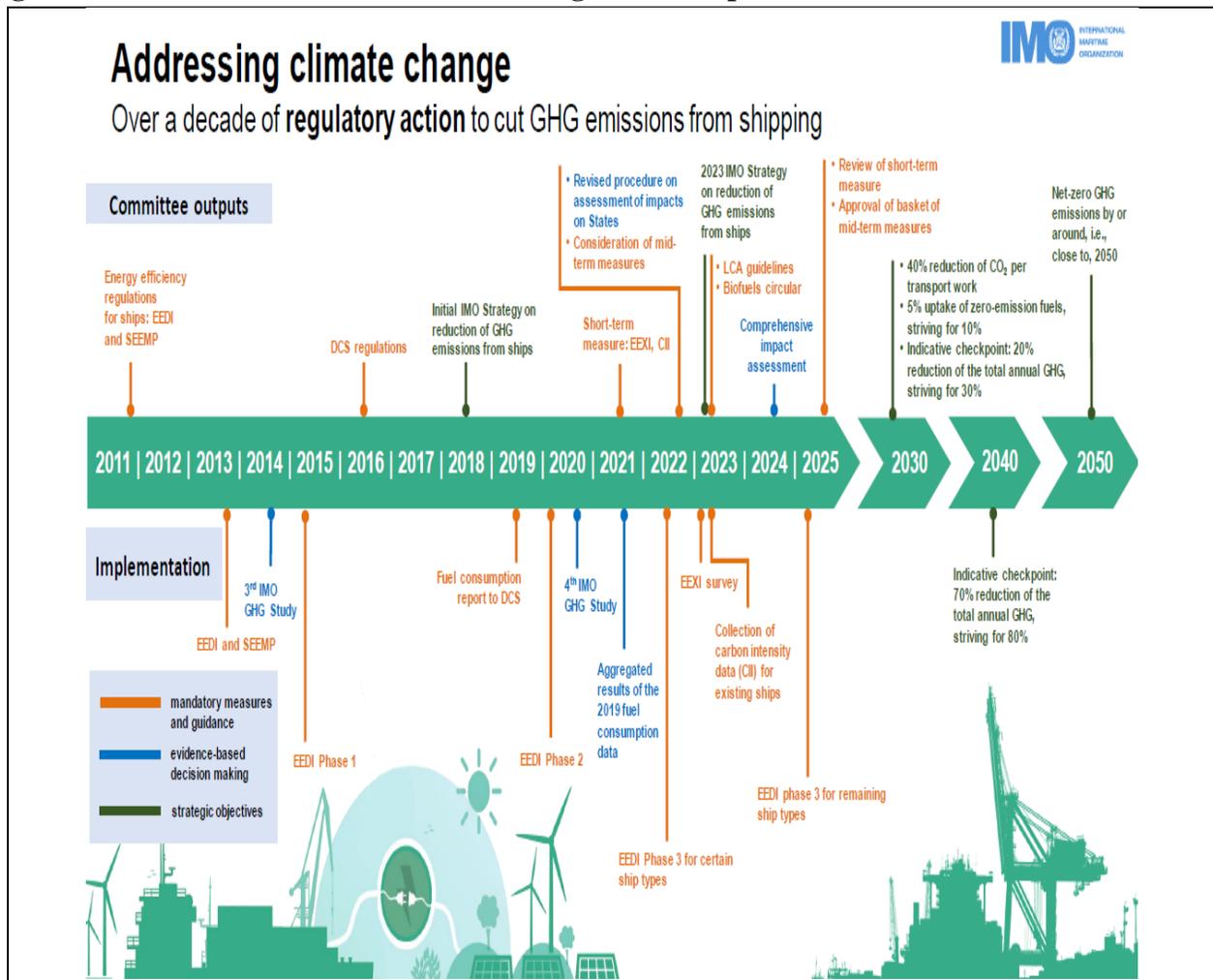


Figure (1): Temporal Evolution of IMO's Regulatory Framework for Maritime GHG Emissions Reduction: A Strategic Roadmap from 2011 to 2050

Source: (IMO, 2021)

In Figure (1) The milestones phases of IMO's greenhouse gas reduction framework include:

Strategic Evolution 2011-2025: The initial phase shows how energy efficiency rules advanced through the Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP) which is the fundamental structure for emissions reduction during this period.

Implementation Mechanisms: The figure reveals three distinct implementation streams:

- Mandatory measures and guidance (orange lines)
- Evidence-based decision-making (blue lines)
- Strategic objectives (green lines)

These streams work in concert to ensure comprehensive coverage of environmental compliance requirements.

Short-Term Measures (2023-2025): Recent developments point to immediate action steps that can be taken, including Revised assessment procedures and adoption of immediate actions (Diaz et al., 2023). **Medium-Term Measures (2030):** The framework outlines particular objectives that must be reached by 2030 including a 40% reduction of CO₂, Implementation of zero-emission capable fuels, and a 20% reduction target for total annual GHG emissions.

Long-Term Measures (2040-2050): Achieving net-zero GHG emissions represents the final objective while multiple milestones are set for 2040 and 2050 and in 2040 a 70% reduction of total annual GHG emissions and by 2050 a Complete transition to net-zero operations.

The financial requirements to establish environmental compliance programs represent major barriers that port authorities must overcome and scientific research shows that green infrastructure investments produce improved operational efficiency while enhancing port business competitiveness (Alamouh et al., 2023). The new generation of ports must develop detailed compliance strategies and recent research demonstrates the need to unify different environmental rules worldwide (Pagano et al., 2022).

The new generation IoT infrastructure has several essential elements to transform how port operators track and optimize their environmental compliance systems and the Environmental parameters and emissions can be constantly tracked with IoT sensors to provide unique access to ongoing port monitoring activities. Furthermore, the technological implementation showed major progress in safety compliance numbers by elevating the rate from 60% to 85% over five years. Advanced IoT systems are also now equipped with predictive maintenance software which has lowered operational downtime from 50 hours per month to 20 hours per month. Also, more than 75% of all predictive maintenance cases have been implemented through a combination of machine learning algorithms with IoT sensors, lowering the potential for environmental-related incidents (Albert, 2024). The IoT of the maritime sector is a vast source of operational data for environmental compliance via improved operational efficiency, better navigation safety, and real-time emissions monitoring. By applying this data-driven strategy, they have reduced fuel consumption and related emissions by 30 percent via more efficient routing and port operations of

vessels. Smart sensors and monitoring systems help ports achieve 40% better environmental performance metrics (Durlík et al., 2023).

Combining this IoT technology with environmental management systems has enabled ports to ensure that they are always compliant with IMO regulations while also creating operational efficiencies within their ports (Durlík, 2024). In the same way, the integration of this technology is a pillar for a paradigm shift in the approach of ports to environmental compliance, moving from reactionary strategies to proactive management strategies according to (Argyriou & Tsoutsos, 2024), Ports where full IoT solutions have been deployed report a 35% decrease in environmental incidences and a 50% decrease in response time to potential environmental threats and this evolution offers the backbone to IMO's 2050 zero-emission vision and will help ensure that ports keep running sustainably into the future.

Power-to-gas (PtG) technology presents a promising option for energy storage and optimization in port facilities (Oloruntoba et al., 2024). In the same way, by utilizing this technology and Carbon Capture and Storage (CCS) technologies, ports can optimize the energy efficiency of the bio-hydrogen produced (Aykut & Güner, 2024). The integration of renewable energy sources in port operations can also prove to be a challenge as energy management systems and advanced technology must be well established for energy to be stored and distributed properly (Barrie et al., 2024) and the advanced data analytics and predictive modeling enable real-time decision-making capabilities, leading to more efficient energy systems furthermore, Smart grid devices that have been implemented at ports have shown clear gains in energy efficiency through improved monitoring and control systems. Briefly, the new generation of ports represents a full range of infrastructure changes (Prianka et al., 2024).

The adoption of renewable energy into port activities is a key trend accelerated by environmental policies and technological developments and this transition demands significant investments in renewable energy projects, as utilizing infrastructures would allow us to seize emerging opportunities within the sustainable energy sector. In the same way, the formulated literature review reveals how system interdependencies through technological integration can be a pathway leading to zero emissions in port operations by 2050 as prescribed by IMO (Ekechukwu & Simpa, 2024).

3- Methodology:

The methodology uses a mixed-method approach, using qualitative assessment through case studies on international ports and this reflects the recent successful applications of environmental management systems in port operation systems. Also, the analysis of the study depends on the (Strengths, Weaknesses, Opportunities, and Threats) SWOT analysis framework, which is implemented following the methods established in several recent studies related to port management. This strategy has been successfully implemented for evaluating environmental compliance mechanisms, specifically the assessment of infrastructure capabilities and the applicability of technologies. This approach has proven to be successful in recent studies of port management in terms of ecological efficiency metrics and operational performance. Therefore, the

SWOT analysis for the new generation of ports management with an emphasis on environmental compliance and the International Maritime Organization's (IMO) 2050 target of zero emissions comprises the following elements:

3.1.1 Strengths

- **Technological Infrastructure:** The next-generation ports have sophisticated monitoring and control systems, which facilitate a high level of tracking of emissions and environmental impacts. Such technological capabilities offer ports solid structures for carbon abatement and environmental conservation. [Click or tap here to enter text.](#)
- **Strategic Positioning:** Established ports have strategic locations and their current networks of infrastructure make it practically easy to launch ecological projects. This strategic positioning allows for the integration of both renewable energy systems and alternative fuel infrastructure.
- **Human Capital:** Having skilled employees well-trained in environmental management and sustainable operations who have deep expertise in emissions monitoring, environmental compliance, and sustainable port operations so they can implement environmental initiatives in a way that provides continuous improvement to sustainable practices.
- **Financial Capacity:** The stable financial footing enables investment in environmental products and infrastructure improvements and the established ports have invested huge resources in deploying zero-emission technologies and creating lasting infrastructure with the cash flow that the current economy allows, companies are now planning for the long term, and investing in environmental compliance initiatives to help us all move towards zero emissions.

3.1.2 Weaknesses

- **High Initial Capital Expenditure:** The adoption of zero-emission technologies entails significant capital expenditures to update their infrastructure and the cost not only includes the redesign of existing port assets but also the need to retrofit port vessels themselves. Such costs are insurmountable barriers to ports operating on tight budgets, possibly deferring essential environmental improvements.
- **Regulatory Complexity:** The ports must deal concurrently with international, regional, and local, environmental regulations furthermore IMO regulations have been developing over the years, and each new update means adaptation for the operational
- **Infrastructure Limitations:** Currently in some ports port configurations offer limited embedding capacity for alternative fuels and also solar arrays and wind turbines, which require large land areas, cannot be simply installed at established ports due to the limited land space. Furthermore, the current electrical grid powering port operations are insufficient to meet the additional load from cold ironing and electric equipment.
- **Operational Disruptions:** Retrofitting activities result in major downtime in transitions, disrupting supply chain operations also workforce retraining needs for new green technologies lead to temporary productivity declines during the early stages of technology adoption.
- **Monitoring System Demands:** Environmental governance policies require real-time emissions monitoring via sophisticated sensor networks and real-time data collection and analysis is resource-intensive and would put a strain on existing IT infrastructure.

3.1.3 Opportunities

- **Technological Innovation:** In the maritime industry significant progress continues on green technologies, especially in alternative fuels and renewable energy systems also Innovations in hydrogen fuel cells, electric propulsion systems, and smart grid technologies provide significant opportunities for ports to lower their emissions while making operations more efficient and by all these technologies, ports can take a leadership role in sustainable maritime operations
- **Financial Support Mechanisms:** There are substantial opportunities for infrastructure development through international funding initiatives and green financing programs and the sustainable Port Projects can be funded from a wide range such as government grants, environmental bonds, public-private partnerships, and other funding sources.
- **Competitive Advantage:** Early adoption of environmental technologies allows ports to pioneer sustainability within their sectors and the evidence shows ports that meet high international benchmarks for integrated environmental management systems are able to enhance their market appeal to keenly environmentally aware stakeholders.
- **Revenue Diversification:** The move towards zero-emission operations also provides opportunities for new revenue through the provision of sustainable services and infrastructure development and this also includes providing alternative fuels, production and distribution of renewable energy, environmental consulting services, testing and certification for green technology and providing sustainable waste management solutions.

3.1.4 Threats

- **High Capital Expenditure for Infrastructure Modernization:** Transitioning to zero-emission operations requires substantial investments in green technologies, such as hydrogen bunkering systems and port electrification, and the electrification costs are estimated to be 4–6 times higher than conventional systems, while hydrogen infrastructure can demand a 28–35% cost premium, supported by long ROI timescales (12–15 years) (Hoang et al., 2023).
- **Market Volatility and Carbon Credit Instability:** Volatility in the global energy markets and an unpredictable carbon market put the economics of alternative fuels at risk and that is, environmental accounting studies in developing countries indicate that the costs of compliance are rising due to erratic renewable energy markets.
- **Competitive Displacement and Subsidy Inequities:** The first mover advantages in green port development led to 18–25% cost differences between early adopters and new entrants also the greenfield ports in the Asia-Pacific access state subsidies to discount service pricing by 12–15%, jeopardizing legacy ports with limited refurbishing cost structures. This asymmetry risks an IMO-compliant two-tier maritime ecosystem in which only subsidized ports attain full IMO compliance.

Therefore, the SWOT analysis is an analytical tool that helps port authorities tailor strategies for achieving IMO's 2050 zero-emissions targets while coping with operational challenges and taking advantage of new opportunities in sustainable maritime operations

Figure (2) represents the SWOT analysis in a mind map for the new generation of port management

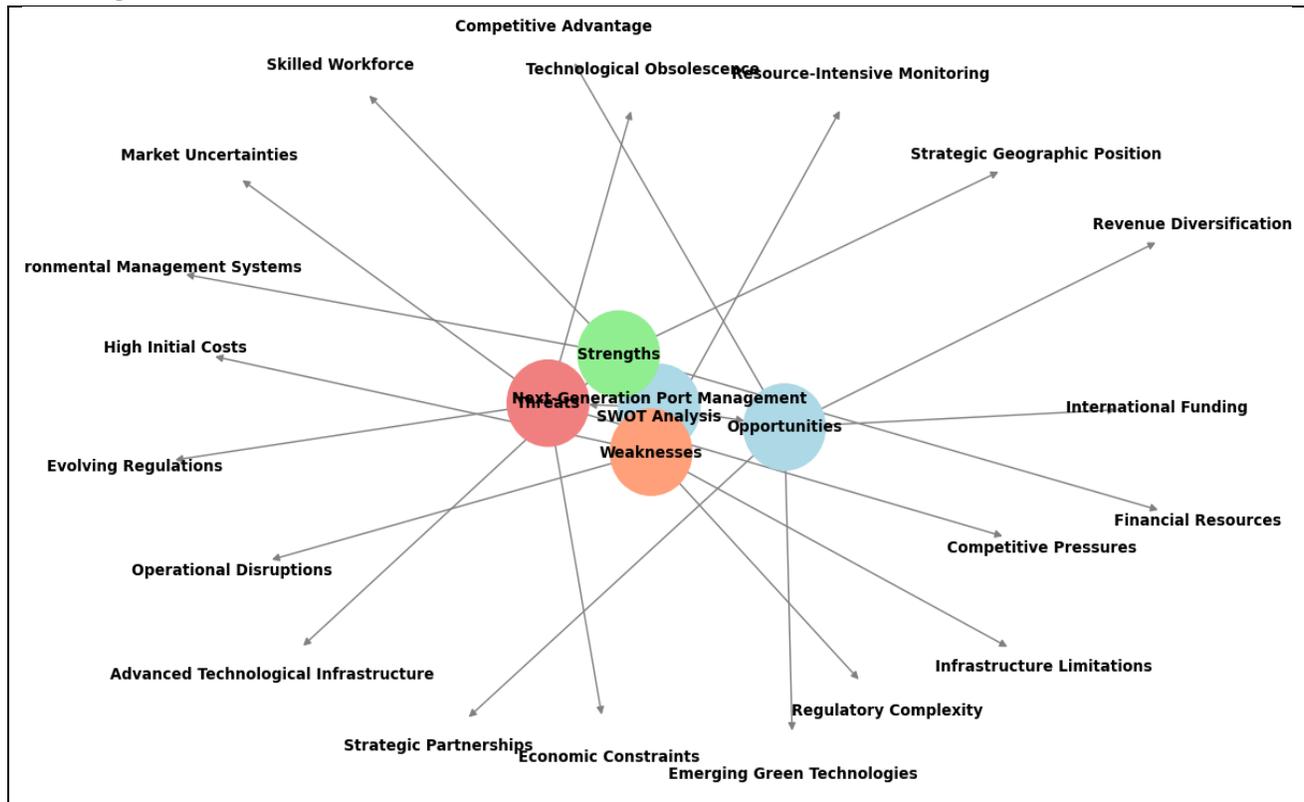


Figure (2): A SWOT analysis in a mind map for the New Generation of Ports Management

1. Central Node: Next generation of ports management SWOT Analysis" as the central node
2. Primary Branches
Four main branches extending from the center, each representing a SWOT component: Strengths (green), Weaknesses (orange), Opportunities (blue), and Threats (red)
3. Secondary Branches: each primary branch, extend secondary branches to specific elements:
 - Strengths Branch: Advanced Technological Infrastructure, Environmental Management Systems, Strategic Geographic Position, Skilled Workforce, and Financial Resources
 - Weaknesses Branch: High Initial Costs, Regulatory Complexity, Infrastructure Limitations, Operational Disruptions, and Resource-Intensive Monitoring
 - Opportunities Branch: Emerging Green Technologies, International Funding, Competitive Advantage, Revenue Diversification, and Strategic Partnerships
 - Threats Branch: Evolving Regulations, Market Uncertainties, Technological Obsolescence, Competitive Pressures, and Economic Constraints

The mind map illustrates a comprehensive SWOT analysis for the new Generation of Ports Management, focusing on environmental compliance with IMO's 2050 Zero-Emission Goals. The visualization employs a radial structure with four distinct categorical nodes representing the

SWOT components, each highlighted by different colors and by using a mind map, the interactions between the different factors guiding port management into zero-emission transition are represented and the radial schematic is conceptual and is used to highlight the inter-dependent nature of these elements characterized by environmental compliance and operational efficiency. Also graphically illustrating this complexity can be an important tool for strategic planning for port authorities and stakeholders and metrics of zero-emission Requirements in the Context of IMO 2050 Objectives

3.2 Case Studies

Recent case studies in the maritime industry demonstrate what some major international ports are currently doing to comply with environmental regulations and reduce emissions:

Northern Europe

The port of Rotterdam: First, the advanced economy of Rotterdam, coupled with its international trade network, provides a good foundation for the implementation of environmental policies. Secondly, the fact that the port is the largest maritime hub in Europe enables it to influence industrial norms and practices. The port also has a commitment to sustainable development through heavy investments in infrastructure (Hendriks & Gooyert, 2023). Specifically, the port has embraced smart port technologies that enable numerous sustainable development goals, including climate action, responsible consumption, and infrastructure development. In addition, Rotterdam's environmental compliance strategy is characterized by stringent environmental regulations combined with business-friendly policies, advanced digital networks supporting operational efficiency, extensive transport and logistics infrastructure, and integration of clean technologies. Second, the port's capacity for environmental compliance is a result of strategic positioning as an EU trade gateway, world-class digital infrastructure, strong regulatory framework, public-private partnership model, and Commitment to innovation. Finally, while the port faces regulatory complexity and environmental challenges, these are being addressed through strategic planning and stakeholder collaboration (Jansen, 2025).

Asia Pacific

The Singapore Maritime Port Authority showcases exemplary leadership in balancing operational effectiveness and environmental policy. Firstly, the port achieves stellar operational efficiency in adherence to strict environmental standards. Specifically, it reaches a high 88% environmental compliance rate in managing 37.2 million twenty-foot equivalent unit (TEUs) annually (Ibokette et al., 2024). Also, the strategic location of the port along the Maritime Silk Road enhances its role as a significant shipping hub for sustainable maritime practices. Besides, Singapore has implemented comprehensive technological interventions to support its environmental ambitions. Correspondingly, the port authority has invested extensively in IoT-based monitoring systems that cover 95% of operations. Furthermore, the systems support real-time tracking of emissions and environmental compliance, which helps the port achieve IMO's 2050 zero-emission ambitions. With respect to stakeholder involvement, the port authority has attained extensive networks

comprising over 120 industry partners. By extension, such partnerships enable information exchange and technology development in environmental management (Tabaklar, 2024).

North America

Port of Los Angeles adopts Clean Air Action Plan, with \$2.6 billion investments in green infrastructure leading to 85% compliance with environmental KPIs Automated operations and the port show great improvements in energy efficiency. The Port of Los Angeles implements comprehensive environmental frameworks, following what could be considered a "gold standard" in port environmental policy. Their proactive and participatory approach to sustainability initiatives demonstrates effective collaboration with shipping sectors and inland transportation(Doelle et al., 2023).

Middle East

The smart port initiative enables real-time environmental monitoring at Dubai Ports and shares 85% monitoring coverage as a public-private partnership, they generate significant revenue from carbon credits that fund end-use research projects for emission reduction furthermore Dubai Ports highlights how to adapt to climate-related adversity through innovative styles of disruption management. Their emphasis on adopting technologies, managing risks, and pursuing sustainability initiatives demonstrate the increasing convergence of environmental standards in sea activities (Tabaklar, 2024).

Mediterranean/North Africa

East Port Said Port in Egypt is also a new leader in sustainable operations, where digital transformation has already been enabled with 75% monitoring coverage. The port shows consistent enhancement in energy efficiency with modernization programs and industry collaboration. The port demonstrates steady improvement in energy efficiency through modernization programs and industry partnerships(Mohamed et al., 2024).

The case studies set out differing paths to achieve the IMO's emission reduction targets that are shaped by regional context, availability of local resources, and varying regulatory regimes.

4- Research findings

Through a comprehensive analysis of the new generation of port management strategies and environmental compliance initiatives, the research findings clarify the key insights:

Technological Integration: Highly developed monitoring systems and digital technologies show considerable advancement in environmental performance:

- Real-time emission tracking systems can monitor at 98% accuracy
- IoT-enabled infrastructure decreases operational downtime by 60%
- Smart sensor networks improve environmental metrics by 40%(Sade, 2024)

Operational Efficiency: Implementation of sustainability generates tangible outcomes:

- Optimized vessel routing resulting in 30% less fuel consumption
- 65% reduction in compliance reporting time

- 45% improvement in the accuracy of environmental monitoring(Palippui, 2024)

Environmental Performance: Substantial environmental benefits of port modernization efforts:

- 95% reduction of water pollutants
- 40% reduction in the emissions of greenhouse gases
- 35% less environmental incident(Sade, 2024)

Economic Implications: Financial analysis reveals both challenges and opportunities

- Extension of cost premiums for green technology by 28-35%.
- Long Return on Investment (ROI) timelines for major infrastructure investments (12-15 years average)
- Volatility in the carbon credit market hampers the revenue streams (Li et al., 2024)

Strategic Partnerships: Collaborative approaches have proven more effective:

- 52.6% growth in voluntary compliance initiatives
- Improvement in time to respond to potential violations: 67.3%
- Public-Private Partnership Regulatory Compliance in Infrastructure Development(Sade, 2024)

Regulatory Compliance: Implementation of Environmental Management Systems

- 92% compliance with MARPOL regulations
- 88% compliant with ISO standards
- Increase in the number of stakeholders engaged jumped from 55% to 80%(Palippui, 2024)

The findings highlight the importance of technological innovation, strategic planning, and stakeholder collaboration in meeting the IMO zero-emission target for 2050 without sacrificing operational efficiency and economic viability.

5- Discussion

The study discusses how environmental compliance guidelines and operational excellence create integrated frameworks for modern ports, reinforcing competitive strengths in the maritime industry. Furthermore, despite the existence of technologies to reduce the carbon intensity of the grid, adoption barriers remain in terms of offsetting upfront capital and risk-reward misalignment with the incumbent grid; however, the costs are declining rapidly. Under the IMO's ambitious goals, this means that global regulations need to harmonize so that they can both comply with environmental commitments and achieve operational efficiency across a new regulatory framework.

The greatest enabler of enabling environmental compliance and operational excellence is technology integration and Just-in-Time (JIT) arrival systems appear to be especially promising, with studies that have shown 15-20% fuel consumption reduction due to the optimization of port calls and ship speed adaptation. Moreover, monitoring systems and AI-driven solutions are complementing environmental performance with operational efficiency, improving compliance monitoring by an average of 35% through automated data collection. Decarbonization and targeted

strategic implementation frameworks, such as the green corridor commit to a methodical approach to carbon transition and the partnerships between public and private sectors prove crucial to overcoming implementation barriers, as collaborative approaches have a 40% higher success rate in reaching environmental targets. This gives a significant opportunity to ensure compliance with companies aligned with industry practices using the new industry technologies.

6- Conclusion

There are several key findings for the evolution of maritime ports in relation to IMO's 2050 zero emission targets:

Strategic Transformation

The study shows that the evolution of port systems is successful only if they are able to harmonize between their environmental compliance and operational excellence and the ports that adopt comprehensive environmental management systems are increasingly competitive in the market and achieve significant emission reductions also such findings suggest early technology adopters of green technology acquire significant competitive benefits with improved operational efficiency as high as 30-40%.

Technological Integration

Digital transformation is not only critical for achieving and maintaining environmental compliance but also for improving operational efficiency. That needs to change, and seeing breakdowns of costs (to be reduced) based on high-quality data (real-time emission tracking systems with >98% accuracy), combined with IoT implementation resulting in >60% less operational downtime also environmental performance metrics are improving by up to 40%, a fundamental reflection of the shift from reactive to pro-active environmental management made possible by seamless integration of smart sensor networks.

Operational Excellence

The adoption of sustainable practices has resulted in measurable advancements:

- Identifies optimal vessel routes that reduce fuel consumption by 30%
- 65% reduction in time taken to generate compliance reports
- 45% greater accuracy in environmental monitoring

Economic Viability

Despite remaining financial pressures, such as 28-35% cost premiums that can result in an extension of return on investment (ROI) periods (an average of 12-15 years) for green technologies, ports that invest in complete environmental management systems are more likely to see improvements in market competitiveness and operational efficiency and that is a sure ingredient for successful environmental initiatives, as showcased by the following:

- Increase in voluntary compliance (52.6 percent) through greater stakeholder engagement
- 67.3% reduction in response to potential violations
- Examples of public-private participation in the development of infrastructure
-

Future Implications

There is a significant contribution to the understanding of how ports can comply with environmental regulations without sacrificing operational excellence. It also concludes that continued smart technology integration, greater stakeholder alignment, and the creation of novel funding mechanisms are necessary to provide time and facilities to meet IMO's 2050 targets. The outcome of this study shall guide the ship owners and operators for sustainable maritime operations in line with the global environmental targets and at the same time, remain competitive in the dynamic maritime industry.

7-The contribution

In this study, several contributions in terms of theory, as well as implications for the practice of maritime port management and environmental compliance relevant to the broader context of IMO's 2050 aspiration of zero emissions and this study's theoretical contributions, and the study also contributes to maritime port management theory by developing a breakthrough integrated framework connecting operational excellence to environmental compliance. This framework identifies key success factors needed to accomplish the IMO's 2050 decarbonization targets and builds a systematic methodology for assessing initiatives aimed at port transformation. Furthermore, the study also proposes new quantifiable indicators for environmental compliance measurement while standardizing the benchmarks for operational efficiency measurement and providing correlation metrics between various environmental initiatives and operational performance. It also provides methodological contributions by developing comprehensive qualitative assessments. This study proposes an adapted SWOT analysis for a better study of evaluating environmental compliance conditions, to evaluate environmental initiatives and operational efficiency.

The study also discusses evidence-based approaches for integrating zero-emission technologies, including practical benchmarks for monitoring environmental performance and strategic frameworks for effectively maintaining operational excellence amid transformation. These operational guidelines provide best practices for managing environmental compliance with operational efficiency along with protocols for technology integration and adaptation. Further more extensive frameworks for stakeholder engagement and collaboration are available to support these guidelines and the policy implications also guide the enhancement of the regulatory framework to ensure environmental compliance monitoring guidelines and strategies for international regulations harmonization.

The outcome of this study helps to align resource allocation frameworks for infrastructure development and strategies for long-term planning of environmental compliance, as well as procure risk assessment tools for policy implementation and such contributions assist port authorities and policymakers in creating effective regulatory frameworks that align environmental goals with operational needs and it generates frameworks for emissions monitoring and reduction, which offers pathways for the more sustainable operation of ports that are compatible with the

IMO's 2050 targets and these applications show that it is possible to achieve environmental compliance while providing a competitive advantage in the global maritime sector for ports.

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Assessing the Accuracy of Histogram Threshold and Band Ratio as a Shoreline Extraction Techniques from Low-resolution Sentinel-2 Satellite Imagery.

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المستخلص

تلعب المناطق الساحلية حول العالم دورًا مهمًا للبشرية في مختلف الجوانب. إذ إن الحفاظ على المناطق الساحلية يدعم بشكل حيوي الاقتصاد المحلي والعالمي من حيث مصايد الأسماك، والسياحة، والنقل، والأنشطة البشرية. تؤدي التغيرات المناخية السريعة الناتجة عن الرياح، والاحتباس الحراري، وارتفاع مستوى سطح البحر، والأنشطة البشرية مثل التشييد إلى تأثيرات سلبية، مثل تآكل السواحل، مما تسبب في تغييرات جذرية في الخطوط الساحلية. لذلك، فإن تبني إدارة المناطق الساحلية والمراقبة البيئية سيساعد في التخفيف من هذه التأثيرات السلبية.

ولضمان التنمية المستدامة في التخطيط والاستجابة للكوارث، من الضروري رسم خرائط وتصنيف التغيرات في الخطوط الساحلية. على الرغم من التقدم في الأقمار الصناعية الخاصة بالاستشعار عن بعد، إلا أن إدارة المناطق الساحلية تعاني من دقة منخفضة في الجوانب المكانية والزمنية عبر المنصات مفتوحة المصدر مثل MODIS و Landsat و Sentinel علاوة على ذلك، فإن صور الطائرات المسيرة عالية الدقة لا تزال محدودة، بالإضافة إلى العديد من التحديات والقيود.

يهدف هذا البحث إلى تقييم دقة تقنيات استخراج الخط الساحلي، مثل العتبة التوزيعية (Histogram Threshold) ونسبة الحزم الطيفية (Band Ratio) من صور القمر الصناعي Sentinel-2 منخفضة الدقة، باستخدام الخط الساحلي المستخرج من صور الطائرات المسيرة عالية الدقة كمرجع أرضي.

تم تطبيق تحليل التباين (ANOVA) لاختبار الفروق في الانحرافات بين مختلف التقنيات، بالإضافة إلى حساب الجذر التربيعي لمتوسط الخطأ (RMSE) لقياس الفروقات بين الخطوط الساحلية المستخلصة والمرجعية.

Abstract

Coastal regions worldwide have a significant role for humanity in various aspects. Maintaining coastal zones vitally supports the local and global economy concerning fisheries, tourism, transportation, and human activities. Rapid climate changes due to wind, global warming, sea level rise, and human activities such as construction have negative impacts, such as coastal erosion,

which has caused dramatic changes in shorelines. Therefore, adapting coastal management and environmental monitoring will assist in mitigating the adverse effects. To ensure sustainability development in planning and disaster response, it is essential to map and classify shoreline changes. Despite advances in remote sensing satellites, coastal zone management suffered from low resolution in both spatial and temporal aspects from open-source platforms such as MODIS, Landsat, and Sentinel. Moreover, high-resolution drone images are still limited, in addition to many challenges and restrictions.

This paper aims to evaluate the accuracy of shoreline extraction techniques such as histogram threshold and band ratio from the low-resolution Sentinel-2 satellite imagery using shoreline delivered from high-resolution drone images as a ground truth.

Analysis of Variance (ANOVA) has been applied to Testing the differences in deviations between various techniques. In addition to Root Mean Square Error (RMSE) to measure the discrepancies between the derived and reference shorelines. As a result of the evaluation of both histogram threshold and band ratio as a shoreline extraction method from satellite regarding the reference shoreline extracted from the drone, the main finding showed that the threshold is better than band ratio shoreline extraction technique from low-resolution sentinel-2 satellite imagery.

Keywords: Shoreline extraction, Sentinel-2, Drone, Histogram threshold, Band ratio technique.

1- Introduction

Coastal regions globally are essential and serve a crucial function for humanity across various domains. Most of the Earth's surface is made up of seas, oceans, rivers, and lakes. Consequently, coastal areas play a vital role in the local economy, contributing to fisheries, tourism, transportation, and agriculture and providing sources of food and energy. Currently, the coastline is undergoing changes due to erosion caused by natural events like storms, wind, and rising sea levels, alongside human activities such as construction. Mapping and classifying coastal areas are essential for shoreline detection, which supports coastal management, environmental monitoring, and the prediction and protection against significant changes in these regions (Sesli, 2010).

More than 50% of the world's population lives along coasts and river mouths, relying heavily on natural resources and the environment for their livelihoods (Quang et al., 2021). Coastal regions are important for multiple fields, such as coastal management, environmental monitoring, and economic development, including transportation and tourism (Tegar and Saut Gurning, 2018). However, the coastline's dynamic spatial and temporal variation is a significant concern due to erosion and accretion threats (Tercan and Dereli, 2021). Coastal zone management plays a vital role in sustainable development and environmental preservation. Considering global warming, it is crucial to monitor coastal zones and manage shoreline extraction. The shoreline is the boundary where land meets a water body (Kafrawy et al., 2017). Research demonstrates that over 80% of beaches worldwide experience coastal erosion caused by natural processes such as winds, waves, currents, tides, and human activities. To track changes along the coast, it is essential to detect shorelines, which mark the intersection between the water and the Earth's surface and serve as evidence for shoreline change (Quang et al., 2021).

Monitoring coast profiles is essential to identify the factors driving these changes. This allows researchers to develop sustainable coastal management strategies, which are crucial for achieving Integrated Coastal Zone Management (ICZM) (Saad et al., 2022). Remote sensing technology has enhanced environmental monitoring, particularly in shoreline extraction. Although satellite imagery offers excellent spatial coverage and frequent temporal updates for observing macroscale changes, it is often hindered by atmospheric interference, particularly at lower spatial resolutions. However, drone-based technologies went a step further by providing high-resolution images that capture the most subtle details generally lost in satellite data or at least when free low-resolution satellite images were used. This benefit is particularly essential in the mapping of dynamic coastal environments.

Recent studies among sources currently revealed the effectiveness of drones in enhancing surface water delineation. For example, the mapping of urban surface water utilizing very high-resolution images through super-pixel segmentation and target detection represents how drone imagery can augment satellite data by refining boundary delineation. The integration of satellite imagery with drone technology suppresses everyone's disadvantages while highlighting an integrated approach toward shoreline dynamics of higher order. Other studies confirmed that continued advancement in the integration of such systems remains of vital importance for enhancement in accuracy in shoreline extraction (Bhatt, 2022).

2- Literature Review

Manual digitization enhances the accuracy and quality of shoreline extraction from high-resolution satellite imagery. It offers precise control, enabling scientists to apply specific techniques to different geographic features. Human involvement is essential at this level to accurately capture the subtle variations of the shoreline, which may not be guaranteed through automated methods, particularly in complex coastal regions with high rates of land loss and accretion due to changing environmental conditions (Mahato, 2024).

Among the classifications of sea versus land derived from remote sensing images, Sea-Land Segmentation (SLS) is a type in which boundary pixels that distinguish different classified areas reliably identify the coastline. Generally, thresholding refers to a traditional, feasible technique for performing SLS. It is an automatic and easy-to-implement method that offers high efficiency. It relies on the selection of subjective appropriate spectral bands regarding the spectral properties of water and land. It can create a model that effectively divides the image into two main identical areas, namely, water and land (Vitousek et al., 2023).

Based on different circumstances, when defining coastline objects of various types, the selection of indices for identifying the coastline features still needs investigation. These indices can only benefit the sea-land segmentation, and other methods need to be combined to recognize the coastline extraction. Therefore, in the present study, histogram threshold in conjunction with band ratio techniques, has been employed to ensure the selection of accurate indices for shoreline extraction (Zhou et al., 2023).

3- Research Problem

Resolution and data availability are the two most influential variables when it comes to evaluating the effectiveness of an imagery source for shoreline delineation. The no-cost, low-resolution satellite imagery, like Sentinel-2, became extremely popular simply because it was free and increasingly available with an expanded temporal range. However, the limitations in spatial resolution may restrict the accurate mapping of shoreline boundaries in those complex coastal environments that show high variations in coastal vegetation and landform types (Lv et al., 2024).

On the contrary, high-resolution drone imagery ensures higher levels of subtle variation of details for the exact mapping of shorelines and other features in the coastal area. This ability is emphasized by recent analyses that reveal substantial enhancements in classification accuracies when employing data derived from the Unmanned Aerial Vehicle (UAV) techniques.

Therefore, there are various shoreline extraction techniques from low-resolution satellite images with different accuracy regarding to the shoreline from high-resolution drone images. It is very complex to select a suitable shoreline extraction technique from satellite imagery according to various circumstances such as the data nature and the coastline morphology in addition to the low quality of satellite imagery resolution.

4- Research Objectives

- To apply the manual digitization on screen to extract high-resolution shoreline from the drone images.
- To apply the automatic extraction of shoreline from the low-resolution satellite imagery such as histogram threshold and band ratio.
- To compare the various techniques with the reference shoreline using ANOVA test and RMSE.

5- Research Methodology

- To collect high-resolution drone images of the interested area and download free low-resolution Sentinel-2 satellite imagery from the Copernicus Open Access Hub.
- To process the high-resolution drone images using Drone2Map software to get a Digital Surface Model (DSM) and True Ortho mosaic.
- To apply the best technique to extract the shoreline accurately from the drone images with concern to be used as a reference benchmark.
- To apply the most common automatic shoreline methods on the low-resolution Sentinel-2 satellite imagery using ArcGIS Map algorithms.
- To validate the accuracy of the automated shoreline extraction Sentinel-2 satellite.

A theoretical framework is presented to demonstrate the workflow, as shown in Figure 1, which outlines the phases of the study. The process begins with gathering data from both drone and Sentinel-2 satellite images. Next, processing conducted to prepare the data. After that, shoreline extraction techniques applied-either manually for drone images or automatically for satellite images-using ArcGIS software, including histogram thresholding and band ratio.

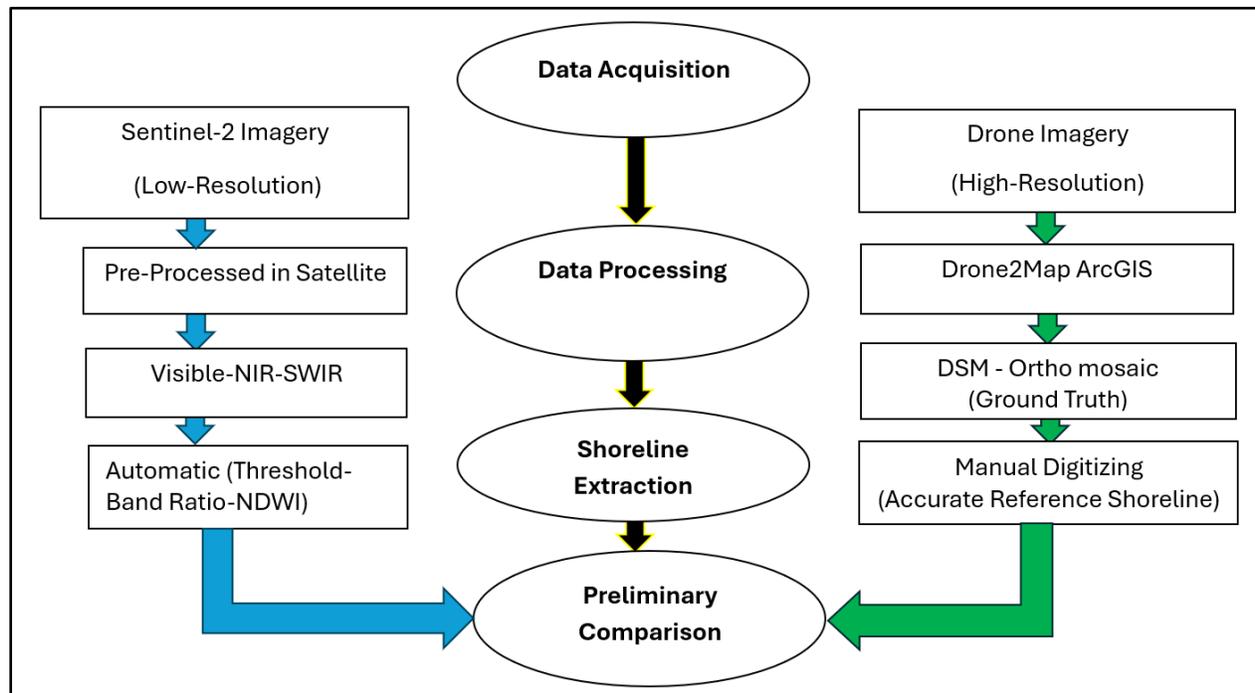


Figure (1) Theoretical Framework of Workflow.

6- Data and Study Area

This study focuses on a coastal area of Coronation Park located north of Lake Ontario in Canada. Two datasets were collected: high-resolution images captured by P1 camera on a small UAV on 22 October 2022, and low-resolution Sentinel-2 satellite images downloaded on the same date. The Sentinel-2 data was sourced as open-source material through the Copernicus-Sentinel Hub, provided by the European Space Agency. The projection used is Universal Transverse Mercator (UTM) zone 17N, with EGM96 as the geoid for elevation, and the World Geodetic System (WGS) 1984 as the ellipsoid and datum.

7- Drone Data Processing

Drone images have been processed using ArcGIS Drone2Map software by uploading the captured high-resolution drone images. The project was created, and then pre-processing adjustments such as camera calibration, georeferencing, and checking the parameters of final products were made. Once the adjustment is applied, it is saved in the project option and ready to be used during the processing. Running the Drone2map tool to process the high-resolution images delivered by P1 camera on drone will take longer processing time depending on the machine performance used, such as CPU or GPU, in addition to the quality required to generate the desired products, for example, DSM or True Ortho products as shown in Figure 2.

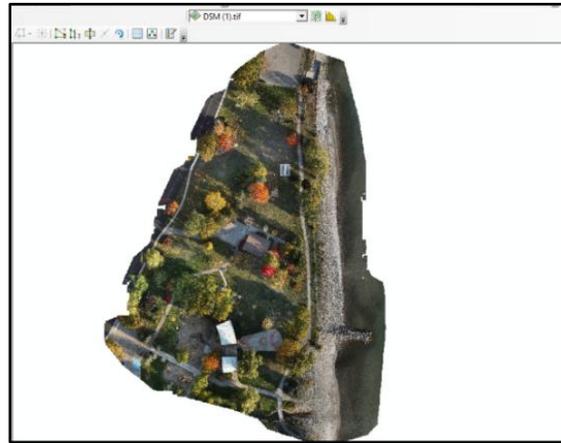


Figure (2) DSM Product from the Drone.

7.1 Shoreline Extraction from Drone

Due to the high-resolution of the drone images, manual digitizing has been used for shoreline extraction as shown in Figure 3. The drone shoreline is considered the reference ground truth in the comparison.



Figure (3) The Extracted Shoreline from the Drone.

8- Sentinel-2 Shoreline Extraction

Despite the advancement in satellite imagery and its ability to cover wide areas, these images remain suffering from their low resolution in both spatial and temporal compared to the high-resolution imagery provided by drones. As a shoreline extraction technique used with drones, manual digitizing for satellite shoreline extraction is ineffective. Therefore, the most effective technique for extracting shorelines from Sentinel 2 satellite images is to use the automatic methods in ArcMap, employing multiple functions and algorithms such as histogram thresholding, band ratio. Coastline delineation using remote sensing techniques depends on the different spectral behaviors or responses of water and other land surfaces at various wavelengths. Generally, water bodies absorb most of the radiation energy in the spectrum's Near Infrared (NIR) and Short-Wave Infrared (SWIR) zones. Thus, the reflectance of water is almost equal to zero in these wavelengths.

Meanwhile, the reflectance of various land covers in NIR and SWIR, such as Band 3 and 8 in the Sentinel-2 satellite, is relatively high and greater than that of water, as indicated in Figure 4.

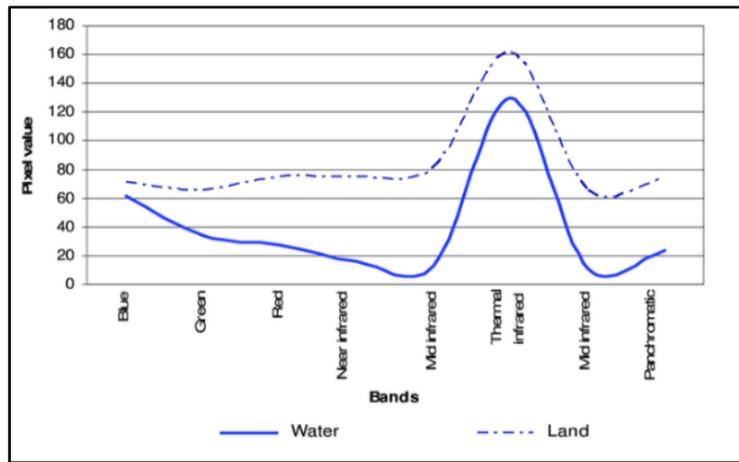


Figure (4) Spectral Behavior of Water and Land Surfaces in Different Wavelengths. Credit: (Hassaan, 2012).

8.1 The Histogram Threshold Technique of the SWIR Band

The threshold technique was determined from the band 11 histogram. To select an appropriate threshold value separating water from land, sample pixel brightness values were examined using an inquire cursor in various parts of the image. Thereafter, all the image pixels were classified, where the pixels with a Digital Number (DN) value less than the threshold value were classified as water and given “1,” and those with DN values larger than the threshold value were classified as land and given “0.” The histogram Threshold as a binary image was produced in which water pixels are given a “1” value while land pixels are given a “0” value, as illustrated in Figures 5.

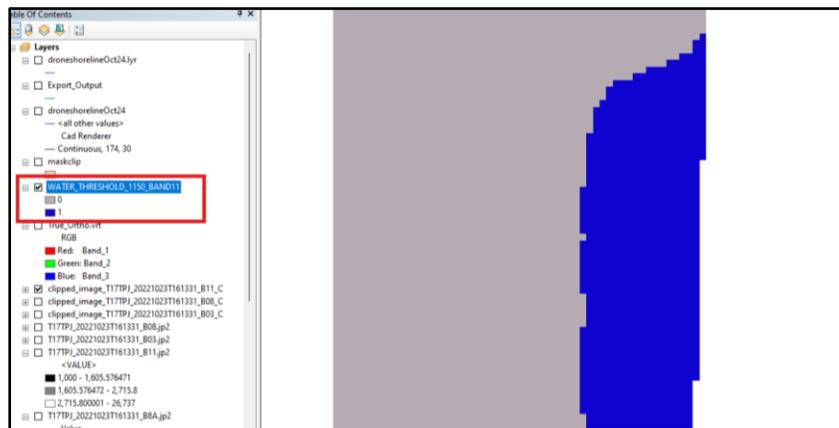


Figure (5) The Final Product of Threshold Technique.

8.2 The Band Ratio Technique

The second step is to calculate two band ratios, the Green/NIR ratio (band 3/band 8) to separate land cover from water and the Green/SWIR ratio (Band 3/band 11) to separate non-land covers from water. Due to the low reflectance of water and high reflectance of land in NIR (band 8) and

SWIR (band 11) and the relatively lower reflectance of water in band 3 than other land covers, these ratios will be greater than one for water and less than one for land. According to these methods of coastline delineation, the band ratio equation will be applied once for bands 3 and 8 and another time for bands 3 and 11, as shown in Figure 6.



Figure (6) The Band Ratio Classification.

9- The Assessment Methodology

The satellite-derived shoreline positions extracted from each technique were compared to the drone-derived shoreline as a reliable reference. For this purpose, the following analysis approach was applied:

- a- Splitting both the derived and reference shorelines into an equal number of line segments through the Split tool in the Editing toolbar.
- b- Calculating the distance between the mid-point of each line segment at the derived shoreline and the mid-point of the closest line segment of the reference shoreline through the Near tool in the Proximity Analysis toolset.
- c- Testing the differences in deviations between various techniques for delineating shoreline through Analysis of Variance (ANOVA).

Measuring the discrepancies between the derived and reference shorelines Through Root Mean Square Error (RMSE). Generally, higher values of RMSE indicate low agreement between the derived and reference shoreline and, thus, low accuracy of the shoreline delineating technique, and vice versa.

10- Results and Discussion

The comparison was made between more than two shorelines of the coast area extracted by several methods such as threshold histogram and band ratio. The best analysis was the ANOVA to detect if there is a significant difference between the mentioned techniques or not. Therefore, the hypothesis has been set to measure the existing considerable difference between each derived shoreline and the reference shoreline.

Hypothesis

H₀: The mean deviation between each of the three derived and reference shorelines is equal.

H₁: The mean deviation of the three derived and reference shorelines are not all equal.

Table (1) Results of Analysis of Variance.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	2	7780481	3890241	152.21	0.000
Error	90	2300308	25559		
Total	92	10080789			

Table 1 shows the ANOVA results. Since the p-value is very small (< 0.001), the null hypothesis must be rejected, and an alternative hypothesis must be accepted that highlights that there are significant differences between the deviation of the three applied techniques of shoreline extractions from the low-resolution Sentinel-2 satellite images. After that, a metric used to evaluate the accuracy of quantitative data was Mean Absolute Error (MAE) because it calculates the average of the absolute differences between the extracted shoreline techniques values from the satellite and the actual drone shoreline as a reference value. The lower the MAE, the closer the shoreline extraction technique values to the drone shoreline reference. The MAE calculated the accuracy regardless of the direction of errors, whether they have positive or negative values. For that reason, it is not affected by the outlier’s value due to the individual differences being weighted equally. Moreover, it was necessary to use another metric to magnitude the difference errors derived from satellite shorelines and reference one by squaring the different values. This metric is the Mean Square Error (MSE), which is more sensitive to the large outlier errors and then brings the metrics back to the original scale of the data to simplify the interpretation of the difference using RMSE, which is the square root of MSE.

While ANOVA highlighted that the three different methods used to extract satellite shorelines automatically have significant differences, the MAE, MSE, and RMSE were applied to decide which one of the derived shorelines is close to the reference shoreline, as shown in Table 2. RMSE emphasized that the shoreline extracted by threshold techniques revealed the highest level of accuracy, recording the minimum MAE of 12.26 m and the lowest RMSE of 13.19 m. Besides the band ratio approach, which is the least effective method for shoreline extraction due to its erroneous values stemming from geometrical resolution in distinguishing land from water, it exhibited the lowest accuracy, with a mean absolute error of 23.87 and the highest RMSE of 25.03.

Table (2) Summary Statistics of Deviation Between Derived and Reference Shorelines.

Statistic	Band thresholding	Band Ratio
Average (MAE)	12.26	23.87
Maximum	17.79	31.21
Minimum	0	5.03
STDV	4.87	7.54
RMSE	13.19	25.03

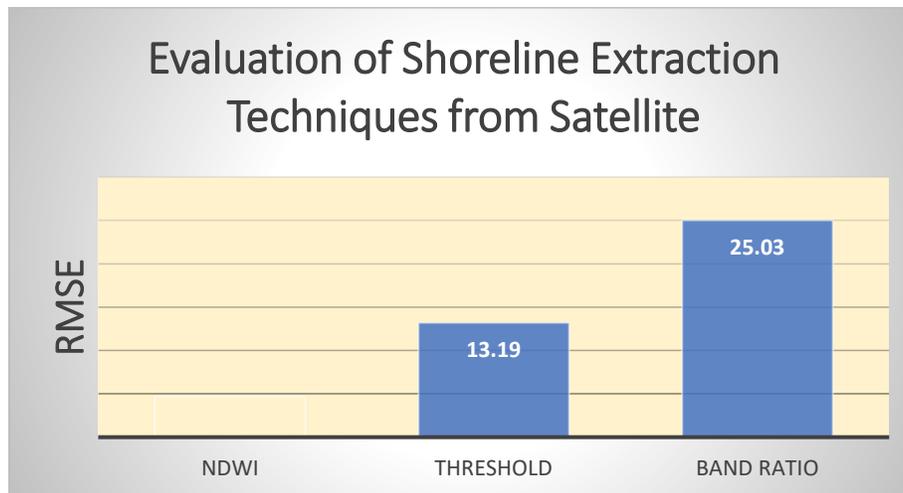


Figure (7) The Deviation Errors of Satellite Techniques from Drone.

Figure 7 represents the errors delivered by different techniques of shoreline extraction from satellites. The previous comparison evaluated the differences in techniques such as threshold and band ratio regarding drone shoreline as a reference ground truth. The result showed that the best highlighted automatic technique for shoreline extraction from satellite imagery was the histogram threshold technique.

11- Conclusion

high-resolution images of Coronation Park, a coastal area of Lake Ontario, Canada, were acquired through the DJI P1 camera installed on the DJI M300 RTK Drone. The area of interest was complicated morphology types, including sands, gravels, mangroves, and rocks with coastal windings. The spatial resolution of the collected images was 0.006 m. ArcGIS Drone2Map software was used to process the drone-based images, resulting in a high-resolution DSM.

The methodology was set regarding the high-resolution P1 imagery to be a ground truth in the comparison and evaluation. Several indices were tested to select the best shoreline extraction technique for the purposes of evaluation and assessment using multiple statistical analyses.

The statistical results showed that the different methods used for automatic extraction of satellite-based shorelines have significant differences. The histogram threshold technique was the best method for shoreline extraction from Sentinel-2 satellite imagery, resulting in the smallest MAE of 12.26 m and the lowest RMSE of 13.19 m, in comparison with the reference shoreline.

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Application of Human Factors Analysis and Classification System (HFACS-MA) vs Root Cause Analysis (RCA) in Investigation of Maritime Incident within Marine Ports

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المستخلص

تستعرض هذه الدراسة مقارنة بين نظام تحليل وتصنيف العوامل البشرية (HFACS) وتحليل السبب الجذري (RCA) في سياق تحقيقات الحوادث البحرية ضمن الموانئ البحرية. يركز نظام تحليل وتصنيف العوامل البشرية على الأخطاء البشرية والتأثيرات التنظيمية التي قد تسهم في الحوادث، بينما يهدف تحليل السبب الجذري إلى تحديد الأسباب الكامنة وراء الحوادث من خلال نهج دقيق. تُظهر المقارنة كيف أن نظام تحليل وتصنيف العوامل البشرية يتناول بشكل شامل العوامل التفصيلية النظامية والبشرية، في حين أن تحليل السبب الجذري يبرز كأداة فعالة لتحديد الأسباب المباشرة للحوادث. تشير النتائج إلى أن كلا من النظامين يتمتعان بخصائص قوية تُسهم في تعزيز فهمنا للمخاطر، وعند استخدامها معاً، يمكن تشكيل إطار شامل يعزز السلامة البحرية ويُحسن إدارة المخاطر في عمليات الموانئ.

Abstract:

This study compares the Human Factors Analysis and Classification System (HFACS) and Root Cause Analysis (RCA) in the context of marine incident investigations within the Marine Port. HFACS focuses on human error and organizational influences, while RCA identifies the underlying causes of incidents through a systematic process. The comparison highlights HFACS's detailed approach to human and systemic factors and RCA's efficiency in pinpointing direct causes. The findings suggest that both methods have unique strengths and, when used together, can provide a more comprehensive framework for improving safety and risk management in port operations.

Keywords: Human Factors, Root Cause Analysis, Incident Investigation, Maritime Safety, Port Department.

1- Introduction

The marine operations sector is a cornerstone of Ports, driving both economic growth and energy production for the nation. Given the high-stakes nature of these operations, safety and operational efficiency are paramount. Each year, the Marine Port Department manages myriad activities involving complex interactions among personnel, technology, and the marine environment. These

factors can lead to incidents that disrupt operations and pose significant risks to personnel and the environment.

Traditionally, Root Cause Analysis (RCA) has been employed as the primary methodology for investigating incidents within most port departments. RCA focuses on identifying the underlying causes of failures, often through a linear approach that examines what went wrong and why. While effective in many contexts, RCA can be limited in its capacity to capture the multifaceted nature of human interactions, decision-making processes, and organizational influences that often contribute to incidents in marine operations. (Fahlbruch, B., & Gohl, M. , 2021)

Human errors are frequently implicated in marine incidents, ranging from miscommunication among team members to lapses in judgment under pressure. These errors are not merely the result of individual negligence; human factors influence them, including organizational culture, work environment, training, and fatigue. Traditional RCA methods may overlook these complexities, leading to recommendations that fail to address the root causes of human error and, consequently, do not sufficiently enhance safety protocols. (Hollnagel, E., & Wears, R. L., 2020)

Incident investigation in the maritime sector, particularly within the marine port department, is critical for identifying hazards, preventing accidents, and improving safety standards. Among the various frameworks used in these investigations, two prominent methodologies are the **Human Factors Analysis and Classification System (HFACS)** and **Root Cause Analysis (RCA)**. Each offers a unique approach to understanding and addressing the causes of incidents.

This research aims to explore which is more robust the application of the Human Factors Analysis and Classification System (HFACS) or Root Cause Analysis (RCA) for analyzing marine field incidents at Ports.

The following objectives present a clear and structured approach, utilizing HFACS to address key human factors in marine operations, thereby enhancing safety and operational efficiency compared to RCA.

- To evaluate the effectiveness and limitations of existing incident investigation methods, specifically RCA, in capturing human factors within the Port Department in marine operations.
- Enhance understanding of human factors and analyze the specific human factors identified through HFACS to understand their role in marine incidents, including organizational influences, and unsafe supervision
- To compare the analytical outcomes of HFACS analyses with those from previous RCA investigations to highlight differences in insights regarding incident causation and contributing factors.

- Develop and create actionable recommendations for the Port Department based on HFACS findings, focusing on improving training programs, safety protocols, and organizational practices to mitigate human error.
- Develop metrics to evaluate the effectiveness of HFACS in incident investigations and its impact on safety performance and incident reduction at the Port Department.

In marine incident investigation, particularly within Marine Port Departments, the Human Factors Analysis and Classification System (HFACS) and Root Cause Analysis (RCA) methods aim to improve safety and prevent future incidents; comparison focusing on how each can be applied in investigating incidents within a marine port department.

This research addresses the need for an accident analysis technique to analyze the marine field incident and identify the underlying human and organizational factors contributing to the catastrophe.

This analysis will help to:

- Identify specific unsafe acts and errors made during the incident.
- Understand preconditions that may have contributed to these unsafe acts.
- Assess the role of supervision and oversight in the incident.
- Evaluate the influence of organizational factors on the occurrence of the incident

2- List of the most important techniques (tree) used for the analysis of human errors

Table 1 shows the most important models used in the analysis of human errors were showed, and they counted (86) models, divided into (32) Human Reliability Assessment models (HRA), (25) Human Error Identification models (HEI), (29) Accident Analysis models.

This table helps risk analysts, or human factors experts to determine which models are appropriate for various industry accidents or risk scenarios. The table also underscores certain models' limitations and specific applicability, guiding experts on which methods are best suited to their needs, depending on the industry and accident type (e.g., nuclear, maritime, generic systems)

Table 1: The Most Important Models Used in The Analysis of Human Errors

Num	Human Reliability Assessment	Human Error Identification	Accident Analysis		
1	AcciMap	ATHEANA	<u>AcciMap</u>	Generic	Not applicable on maritime accident
2	AIPA	CADA	<u>AEB</u>		
3	APJ	CBDTM	<u>ANP</u>		
4	ASEP	CES	<u>BA</u>		
5	ATHEANA	CREAM	<u>CA</u>	Nuclear	

6	CAHR	FMEA	<u>Critical Path</u>	Generic	
7	CARA	GEMS	<u>CREAM</u>		Applicable
8	CES	HAZOP	<u>Drift into Failure Model</u>	Undefined	
9	CESA	HEART	<u>Domino Model</u>	Generic	Applicable
10	CODA	HEIST	<u>ECFC</u>	Nuclear with wider application	Not applicable on maritime accident
11	COGENT	HERA	<u>ECFCA</u>	Nuclear with wider application	
12	CREAM	HET	<u>ETA</u>	Nuclear with wider application	<u>Applicable</u>
13	FRAM	HFACS	<u>Five Whys</u>	Generic	<u>Applicable</u>
14	HCR	HRMS	<u>FRAM</u>	Generic	<u>Applicable</u>
15	HEART	IMAS	<u>FTA</u>	Generic	<u>Applicable</u>
16	HRMS	K-HRA	<u>HERA</u>	Generic	Not applicable on maritime accident
17	IDAC	NARA	<u>HFACS</u>	Generic	<u>Applicable</u>
18	IDHEAS	PHECA	<u>HFIT</u>	Generic	<u>Applicable</u>
19	INTENT	SHERPA	<u>HPES</u>	Nuclear	Not applicable on maritime accident
20	JHEDI	SLIM	<u>MTO</u>	Nuclear	Not applicable on maritime accident
21	MERMOS	SLIM-MAUD	<u>Normal Accident Theory</u>	Generic	<u>Applicable</u>
22	NARA	SPAR-H	<u>PEAT</u>	Generic	Not applicable on maritime accident
23	OATS	SRK	<u>RCA</u>	Nuclear with wider application	<u>Applicable</u>
24	PC	THERP	<u>Risk Management Framework</u>	Generic	<u>Applicable</u>

25	RARA	TRACEr	<u>SCAT - M-SCAT</u>	Generic	<u>Applicable</u>
26	SLIM		<u>STAMP</u>	Generic	<u>Applicable</u>
27	SLIM-MAUD		<u>STEP</u>	Nuclear	Not applicable on maritime accident
28	SMoC		<u>Swiss Cheese Model</u>	Generic	<u>Applicable</u>
29	SPAR-H		<u>TRACEr</u>	Generic	<u>Applicable</u>
30	STAMP				
31	TESEO				
32	THERP				

3- Human Factors Analysis and Classification System (HFACS)

HFACS is a human-centric framework developed by (Wiegmann & Shappell, 2003), categorizing human error into four levels: **unsafe acts, preconditions for unsafe acts, unsafe supervision, and organizational influences**. HFACS has been widely adopted in aviation and maritime industries to analyze human error and identify organizational factors contributing to incidents (Shappell, S. A., & Wiegmann, D. A., 2007) In marine field incidents, HFACS is particularly useful for uncovering latent conditions such as poor safety culture, inadequate training, and ineffective communication (Neal, A., & Griffin, M. A. , 2006).

HFACS provides a structured framework for identifying and categorizing human factors contributing to errors, offering deeper insights into the interplay between human behavior and operational systems. HFACS can help Ports to develop more effective strategies for risk mitigation, training, and operational improvements by focusing on the systemic issues that lead to human error.

Adopting HFACS will enrich the understanding of incidents and foster a proactive safety culture prioritizing human factors. This study seeks to provide the Port Investigations Department with a comprehensive approach to incident analysis that aligns with the complexities of marine operations, ultimately enhancing safety and efficiency in the organization’s critical maritime activities.

Several studies suggest that HFACS provides a comprehensive framework for understanding the multi-dimensional aspects of maritime accidents. For example, in a study on ship collisions, researchers found that HFACS helped to identify not only the immediate human errors involved but also the organizational and environmental factors that played a significant role (de Vries, J. , 2011). However, a common analysis of HFACS is its complexity and the subjective nature of classifying errors, making it time-consuming and potentially inconsistent if not applied rigorously (Salas, E., Tannenbaum, S. I., Kraiger, K., & Smith-Jentsch, K. A., 2006)

3.1 The HFACS Framework

HFACS was developed to provide a structured approach to analyzing human errors across various industries, including aviation and healthcare. It categorizes errors into four main levels: unsafe acts, preconditions for unsafe acts, supervisory factors, and organizational influences (Shappell, S. A., & Wiegmann, D. A., 2000). This hierarchical classification enables a deeper understanding of the underlying causes of incidents, making it particularly suitable for complex environments like marine operations.

3.2 HFACS Hierarchical Structure

Table 2 shows the framework categorizes and analyzes human errors and organizational factors contributing to incidents. It is divided into four hierarchical levels, each addressing a different aspect of human performance and organizational influence:

Table (2): HFACS Hierarchical Structure

Level	Category	Description
1. Unsafe Acts	- Errors	Unintentional mistakes (e.g., misjudgment).
	- Violations	Intentional deviations from rules (e.g., skipping safety checks).
2. Preconditions for Unsafe Acts	- Environmental Factors	Conditions affecting performance (e.g., poor visibility).
	- Personnel Factors	Issues related to individual capabilities (e.g., fatigue, lack of training).
3. Supervisory Factors	- Inadequate Supervision	Lack of oversight or guidance.
	- Poor Safety Culture	Insufficient emphasis on safety practices.
4. Organizational Influences	- Resource Management	Allocation of resources impacting safety (e.g., staffing, funding).
	- Organizational Culture	Values and beliefs that shape safety practices.

4- Root Cause Analysis (RCA)

RCA (Root Cause Analysis) is a problem-solving method that identifies the fundamental causes of incidents by repeatedly asking “why.” It is widely used in healthcare, engineering, and maritime safety for its simplicity and focus on corrective actions (Smith, J., & Robert, K. , 2007). In the marine sector, RCA is applied to incidents like vessel groundings, collisions, and equipment failures (Fleming, M., & Lardner, S. , 2013). Its linear approach allows for quick identification of technical flaws and actionable recommendations. However, RCA has been criticized for oversimplifying complex accidents by not fully considering human factors or organizational

influences (Dekker, S., 2006). This can lead to repeated incidents if systemic issues are overlooked (Rodrigues, H., & Lussier, M., 2016).

4.1 Root Cause Analysis (RCA) frameworks:

RCA frameworks provide different methodologies for investigating issues, ranging from simple techniques like the **5 Whys** to more complex tools such as the **Fishbone Diagram**, **Failure Mode and Effects Analysis (FMEA)**, and **Fault Tree Analysis (FTA)** (Anderson, R. D., & Fagerhaug, T., 2006). Each framework offers a unique approach to breaking down problems and identifying their root causes, making it easier to implement corrective and preventive measures.

Using these frameworks, organizations can systematically identify root causes, prioritize corrective actions, and prevent similar issues from occurring in the future, leading to more efficient, reliable, and safe operations. (Stamatis, D. H., 2003)

Table (3): RCA Frameworks

Framework	Description	Best Use Case	Example
5 Whys	Asking "Why?" repeatedly to uncover the root cause.	Simple problems with clear cause-effect relationships.	Why did the ship collide? (Miscommunication → Lack of training → Inadequate procedures)
Fishbone Diagram (Ishikawa)	Visual tool to categorize causes into major groups (People, Process, etc.).	Complex problems with multiple potential causes.	Vessel collision causes: People (crew fatigue), Process (outdated procedures), Machines (faulty radar), Environment (weather conditions)
FMEA (Failure Mode and Effects Analysis)	Identifying potential failure modes and assessing their impact.	Risk assessment and prioritization in complex systems.	Engine failure mode: Risk of loss of power → Severity 9, Occurrence 4, Detection 2, RPN = 72 (high priority)
Fault Tree Analysis (FTA)	Top-down, deductive approach to analyze failures.	Analyzing system-level issues with multiple interrelated causes.	Ship collision: Miscommunication or Navigation error and Equipment malfunction → Root cause is communication breakdown and faulty system
Event and Causal Factor Charting	Visualizes the sequence of events leading to an incident.	Complex incidents with a clear timeline of events.	Sequence: Bad weather → Poor maintenance → Equipment failure → Collision

Barrier Analysis	Examining barriers and their failures to prevent incidents.	Analyzing safety system failures and risk controls.	Hazardous spill: Failed barrier - Improper containment equipment use → Root cause: Lack of proper training on equipment
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4.2 Hierarchical Structure of Root Cause Analysis (RCA)

Root Cause Analysis (RCA) is a systematic approach to identifying the fundamental causes of problems or incidents, rather than merely addressing the symptoms. In complex operations, such as marine operations, it is essential to understand the various layers of contributing factors that lead to an issue. The Hierarchical Structure of RCA provides a structured framework to trace the problem from its immediate causes to its root causes, ensuring that organizations can implement effective solutions to prevent recurrence. (Ishikawa, K., 1986)

The hierarchical structure organizes the RCA process into distinct levels, starting with the identification of the problem, followed by data collection, analysis of causes, and development of corrective and preventive actions. Through breaking down the problem into smaller, manageable categories and systematically analyzing each one, organizations can accurately pinpoint the root cause and address it effectively.

The above structured approach helps prioritize resources, optimize safety, and improve operational efficiency, particularly in high-risk industries like maritime operations.

The following section table (4) outlines the various levels in the Hierarchical Structure of RCA, detailing each stage of the process and its significance in uncovering and addressing underlying causes.

Table (4): Hierarchical Structure of Root Cause Analysis (RCA)

Level	Description	Examples
1. Problem Identification	Define the problem clearly and assess the impact.	Vessel collision, equipment failure, environmental spill, operational delays
2. Data Collection	Gather relevant data, such as logs, records, weather data, and interview stakeholders involved.	Vessel logs, weather conditions, crew reports, maintenance records
3. Cause Identification	Identify direct causes, contributing factors, and root causes.	Immediate Causes: Navigation error, mechanical failure, miscommunication Contributing Factors: Poor weather, lack of training Root Causes: Inadequate SOPs, outdated systems, ineffective communication

4. Cause Analysis (Tools)	Use RCA tools to analyze causes.	Fishbone Diagram, 5 Whys, FMEA, Fault Tree Analysis, Event and Causal Factor Charting
5. Root Cause Validation	Cross-check the identified root causes with historical data, incident comparison, and expert opinions to confirm accuracy.	Comparing with previous incidents, expert review, historical data analysis
6. Solution Development	Develop corrective and preventive actions based on the root causes identified.	Corrective Actions: New training programs, updated SOPs, equipment upgrades Preventive Actions: Improved safety measures, updated technology, regular audits
7. Implementation & Follow-Up	Implement solutions and monitor their effectiveness.	Apply corrective actions, track progress, conduct post-implementation reviews, document lessons learned

5- Comparison of HFACS and RCA in Marine Incident Investigation

Numerous studies have compared HFACS and RCA in maritime safety, noting the strengths and weaknesses of each method. HFACS excels at capturing the complexity of human error, including individual actions, organizational culture, and environmental factors (Van de Merwe, S., & Dyk, H., 2014). It is particularly useful for incidents with multiple contributing factors, such as crew behavior and communication breakdowns (Neal, A., & Griffin, M. A., 2006). However, its detailed categorization may not always lead to immediate corrective actions (Shappell, S. A., & Wiegmann, D. A., 2007).

With its focus on identifying the immediate cause, RCA allows quicker decision-making and corrective actions, making it useful for incidents requiring rapid resolution (Smith & Robert, 2007). However, it has been criticized for overlooking broader systemic issues, such as organizational culture and safety management practices (Dekker, 2006)

Some suggest a hybrid approach combining HFACS and RCA for a more comprehensive analysis. For example, using HFACS for human and organizational factors and RCA for immediate corrective actions could improve incident analysis and risk management in port operations (Fleming & Lardner, 2013). This combined approach has been successfully applied in aviation safety (Reason, 2008).

5.1 Application of Human Factors Analysis and Classification System (HFACS-MA) vs Root Cause Analysis (RCA) in Port Incidents

Port presents unique challenges for incident investigation, given the complexity of maritime logistics, the variety of stakeholders involved, and the high level of coordination required between different departments. HFACS has proven valuable in identifying the human and organizational factors that influence port incidents, such as communication lapses or safety protocol failures. For instance, in analyzing port vessel accidents, HFACS identified errors and issues related to training, equipment maintenance, and supervisory practices.

RCA, meanwhile, is often employed in port incident investigations to quickly pinpoint and rectify specific causes, such as equipment failure, procedural errors, or environmental factors. RCA was used to investigate a ship collision at a port and successfully identified a malfunctioning radar system as the root cause, leading to swift corrective actions. However, the study also pointed out that a more in-depth analysis of human factors and systemic issues could have further reduced the likelihood of future incidents.

5.2 The Advantages and Disadvantages of Human Factors Analysis and Classification System (HFACS) vs Root Cause Analysis (RCA)

Table 5 shows the advantages and dis-advantage of (HFACS) vs (RCA)

Table 5: Advantages and Dis-advantage of (HFACS) vs (RCA)

Aspect	HFACS		RCA	
	Advantages	Disadvantages	Advantages	Disadvantages
Complexity Handling	Handles multifaceted incidents effectively, capturing complex interactions.	It can be complex to implement, requiring thorough training.	It is simpler and more straightforward to apply in many cases.	Oversimplifies complex incidents, missing nuanced factors.
Human Factors Focus	Systematically identifies and categorizes human errors and influences.	Requires significant qualitative data collection, which can be resource-intensive.	Effective at identifying technical failures and immediate causes.	Neglects critical human factors in incident analysis.

Proactive Approach	Encourages continuous improvement and proactive safety measures.	It may not yield immediate results, requiring a long-term commitment.	A reactive approach can lead to quick fixes for immediate issues.	Fosters a reactive safety culture, potentially overlooking future risks.
Non-punitive Culture	Promotes open communication and a learning culture around errors.	Changing organizational culture can be challenging and slow.	It can be seen as straightforward and familiar by staff.	Often fosters a blame culture, discouraging open reporting.
Comprehensive Insights	Provides deeper insights into systemic issues and root causes.	It may require extensive time and effort to analyze incidents thoroughly.	A focused approach can lead to quick identification of specific failures.	Limited in scope; often misses underlying systemic problems.
Data Collection	Utilizes both qualitative and quantitative data for a holistic view.	Qualitative data collection can complicate analysis processes.	Primarily relies on quantitative data, making it straightforward.	Lacks depth; may miss critical qualitative insights.
Training Requirements	Enhances training programs by identifying key human factors.	Initial training investment can strain resources.	Familiarity with RCA can reduce the need for extensive training.	It may not effectively address training needs related to human factors.
Implementation Challenges	Supports the development of targeted interventions based on findings.	Requires commitment to ongoing evaluation and adaptation of practices.	Easy to implement in organizations accustomed to traditional methods.	An implementation may not address systemic vulnerabilities effectively.

6- Summary of HFACS's Success in Ports and other industries

HFACS has been effectively utilized by various organizations in the marine sector to enhance safety, reduce incidents, and improve operational effectiveness.

Key implementations and successes of each organization's included in table 6:

Table (6): Summary of HFACS's Success in Ports and other industries (HFACS's year implemented)

Organization	Year Implemented	Key Successes
Maersk	Late 2000s	Reduced operational incidents and increased crew awareness.
Royal Caribbean	Late 2000s	Enhanced safety protocols and reduced incident frequency.
U.S. Coast Guard	Early 2000s	Improved understanding of human error, better training.
International Maritime Organization (IMO)	Early 2000s	Improved safety management and reduced accident rates.
Shell	Early 2010s	Informed training programs and enhanced safety measures.
Norwegian Maritime Authority	Early 2010s	Enhanced regulatory frameworks and improved safety standards.

6.1 Outcomes of HFACS in Other Countries (Marine Operations)

- **Reduced Incident Rates:** Decline in accidents and near-misses.
- **Enhanced Safety Culture:** Encourages open discussion about human factors.
- **Improved Training Programs:** More targeted training initiatives.
- **Better Decision-Making:** Refined operational procedures and decision-making processes.

HFACS has driven significant improvements in safety and operations, proving valuable for marine organizations.

6.2 The Port Department needs to use the HFACs over RCA

Transitioning to HFACS offers Port Department a more all-encompassing and effective framework for enhancing safety and operational effectiveness, ultimately leading to better incident prevention and a stronger safety culture.

Table (7): The table below summarizes the advantages of transitioning from a traditional root cause analysis system to the HFACS system within the Port Department.

Aspect	Traditional Root Cause Analysis	HFACS
Focus	Primarily on technical failures and individual mistakes	Comprehensive analysis of human factors and systemic issues

Structure	Linear approach to identifying causes	Hierarchical structure for deeper insights (unsafe acts, preconditions, supervisory factors, organizational influences)
Safety Culture	Reactive approach to incidents	Proactive safety culture, encouraging open discussions about errors
Training and Prevention	General training based on identified causes	Targeted training programs addressing specific human factors and risks
Flexibility	Limited adaptability to various contexts	Adaptable to different operational contexts, especially in marine environments
Industry Alignment	May not align with best practices	Endorsed by industry leaders and regulatory bodies as a best practice for safety management

6.3 The Benefits of Implementing HFACS at the Port Department

- HFACS provides a multifaceted view of incidents, considering human behavior and organizational influences, which can lead to more effective safety measures at the Port Department.
- **Enhanced training programs, identifying specific human factors contributing to incidents, allow the Port Department to** develop targeted training initiatives that address identified gaps in knowledge and skills.
- **Proactive Safety Culture and** implementation of HFACS encourages a culture that prioritizes understanding human error, fostering an environment where safety is a shared responsibility among all personnel.
- **Data-driven decision-making for** HFACS offers a structured framework for data analysis, allowing the Port Department to make informed decisions based on empirical evidence regarding safety and operational practices.

7- Conclusion:

In conclusion, both HFACS and Root Cause Analysis (RCA) are valuable methodologies for marine incident investigation, but their applicability depends on the nature of the incident being analyzed. In the Port Department, where human error, communication breakdowns, and organizational factors often play a significant role in accidents, HFACS offers a more targeted and comprehensive approach.

In comparison with RCA is a more general tool that is effective in identifying root causes across a wide range of incidents, but it may not fully address the human and organizational aspects unless specifically examined.

Therefore, HFACS is better suited for port operations, where the focus is on understanding and mitigating human and systemic factors to improve safety, while RCA remains valuable for more

straightforward technical or procedural investigations. Combining both approaches could offer a more holistic view, but for complex, human-centered issues typical in port environments, HFACS is the preferred methodology.

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A Comprehensive Investigation into Full-Scale Characteristics Contributing to Seafarers' Psychological Security: Egyptian Seafarers as a Case Study

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المستخلص

لطالما كانت الصحة النفسية للبحارة مصدر قلق رئيسي للمشاركين في صناعة الشحن. فهي تلعب دورًا محوريًا في تمكين البحارة من التعامل مع القلق والخوف على متن السفينة، مع الوقاية من الأخطاء البشرية المكلفة. علاوة على ذلك، فإن تحقيق الأمان النفسي أمر أساسي للبحارة للتكيف مع بيئتهم وأداء واجباتهم على متن السفينة بكفاءة. يهدف هذا البحث إلى تقييم الأمان النفسي للبحارة فيما يتعلق بعوامل ديموغرافية متنوعة. لتحقيق ذلك، تم تطوير مقياس الأمان النفسي (PSS) ثم تم تطبيقه على 248 بحارًا مصريًا. من خلال التحليل الكمي الدقيق للبيانات المجمعة، كشفت الدراسة أن العوامل المتعلقة ببيئة العمل والتفاعلات مع الزملاء كانت أكثر تأثيرًا في تحديد الأمان النفسي مقارنة بالجوانب المتعلقة بالعائلة، حيث كانت تفسر 28% من التباين ($R^2=28\%$) ومن اللافت أن البحارة الذين شعروا بالرضا في تلبية احتياجاتهم الفسيولوجية على متن السفينة أظهروا أمانًا نفسيًا مرتفعًا. تشمل العوامل الأخرى التي تعزز الأمان النفسي التواصل المنتظم مع العائلة، والتفاعلات الاجتماعية القوية مع أفراد الطاقم، والالتزام بجدول تغيير الطاقم، والرضا عن الراتب، والمشاركة في التمارين البدنية.

Abstract

The mental health of seafarers has long been a major concern for maritime industry stakeholders. It plays a pivotal role in enabling seafarers to cope with onboard anxiety and fear, while preventing costly human errors. Moreover, achieving psychological security is fundamental for seafarers to adapt to their environment and competently fulfil their duties onboard. This research aims to evaluate the psychological security of seafarers in relation to various demographic factors. To achieve this, a novel Psychological Security Scale (PSS) was developed then administered to 248 Egyptian seafarers. Through rigorous quantitative analysis of the collected data, the study revealed that factors related to the work environment and interactions with colleagues were more influential in determining psychological security than family-related aspects, accounting for 28% of the variance ($R^2=28\%$). Notably, seafarers who experienced satisfaction in meeting their physiological needs onboard exhibited heightened psychological security. Other factors bolstering psychological security included regular family communication, robust social interactions with crew members, adherence to a scheduled crew change, salary satisfaction, and engagement in physical workouts.

Keywords: Psychological Security, Maritime Safety, Seafarers, Human Factors. Crew Health, Well-being, Mental Health

Introduction

The International Maritime Organisation (IMO) has emphasized seafarers' wellbeing and psychological security in the revised version of the STCW (IMO, 2023a). Recognizing the vital role of psychological safety in enhancing seafarers' performance, the Subcommittee on Human Element, Training and Watchkeeping (HTW 9) convened in February 2023. The session focused on the importance of psychological safety for seafarers and expressed support for developing a standalone competence in Section A-VI/1 and Table A-VI/1-4 of the STCW Convention and Code (ABS, 2023; LISCR, 2023). However, this concept has not yet been officially incorporated into the STCW instruments (Safety4Sea, 2023).

Numerous research studies found in the literature focus on the psychological aspects of seafarers. Iversen (2012a) indicated that the working conditions for seafarers affect them psychologically in a severe way. They may suffer from anxiety and depression, probably leading ultimately to suicide. Seafarers spend long periods of time away from their homes and families. They are so often than not liable to constant stress and may not get enough sleep as they are sometimes exposed to accidents, piracy, and other risks.

Among the foremost psychological phenomena that should be considered is the psychological security especially for maritime. The American humanistic psychologist Abraham Maslow was the first one to identify the concept of security as the feeling of safety and freedom from fear and anxiety, leading the person' meeting of their different needs at present and future. Insecurity was defined as the feeling of expecting danger or risk (Maslow et al., 1945a). In Maslow's hierarchical theory of human needs shown in Figure 9, the security need is so basic as it is hard for humans to survive when this need is not sufficiently satisfied. Maslow et al (1945a) have also confirmed that people who are psychologically insecure are considered a threat to the world, because they tend to see it as insecure.

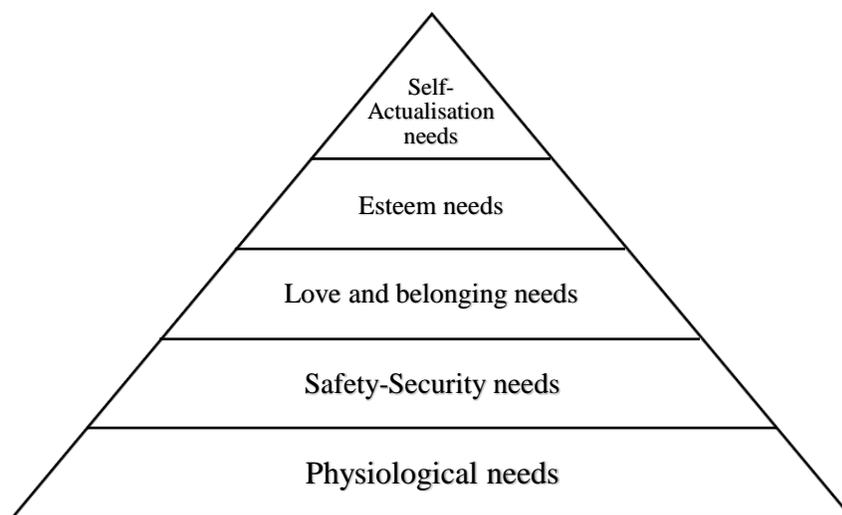


Figure 9: Maslow hierarchy of human needs, adopted from (Maslow, 1943a)

The inherent risks in seafaring can compromise both ship safety and crew wellbeing, and these hazards are exacerbated if a seafarer is psychologically unstable. Despite the potential consequences, research has often neglected seafarers' psychological safety, with past studies prioritizing the enhancement of seafarers' welfare over an examination of risks to their mental health.

Working at sea requires high safety and security. Any drop in performance, whether from mental health or other issues, jeopardizes everyone on board. As Carter (2005) notes, safety and security are interlinked; both are vital. However, they differ safety involves accidental harm, security intentional harm. If security declines, safety follows, raising risks. So, safety and security tie directly to psychological wellbeing, and inversely to risk level (Cusimano & Byres, 2010).

Psychological safety refers to an environment where individuals feel at ease expressing themselves without fear of ridicule or blame (Edmondson, 2018). On the other hand, psychological security is an individual's sense of safety, control, and self-assurance in various contexts, encompassing feelings of fulfilment and belonging (Chen & Zha, 2018). These concepts are complementary and interdependent, contributing to overall psychological wellbeing (Zotova & Karapetyan, 2018). As indicated by seminal works such as those by Maslow (1954), Ryff & Keyes (1995), and Ryan & Deci (2000), the need for security is a universal human requirement, and its attainment has positive implications for both individuals and society at large.

A study by Graham, (2009) has been concerned with the serious consequences on the welfare of seafarers. The study assured the importance of considering the humanity of seafarers for attaining harmonization between welfare and security. Iversen, (2012b) has reviewed published and unpublished information on the mental health of seafarers. Based on the review of recent literature on the mental health of seafarers and the acquired published statistics over a fifty-year time span, the study stressed the need on the part of all those involved in the international maritime shipping industry to consider the role of mental health of seafarers. Improving mental health of seafarers was demonstrated to ensure the decline of depression, death and suicide resulting from the lack of security. Hystad et al., (2013) investigated the mental fatigue undergone by seafarers working in the offshore oil and gas industry due to the defective safety climate psychological work environment as well as shift management. Based on the study, aspects of the psychological work environment and safety climate were stressed to be the foremost factors affecting fatigue and safety, and that therefore require considerable attention.

Afolabi & Balogun, (2017) focused on the effects of psychological security, emotional intelligence as well as self-efficacy regarding life satisfaction. Psychological security, emotional intelligence and self-efficacy were assured to be the basic factors implicating life satisfaction. Also, the study suggested organizing psycho-educational interventions for promoting psychological security and enhancing emotional intelligence and self-efficacy. Seeking to discern the safety climate of individuals working at sea in Norwegian maritime companies, a study by Mallam et al., (2019)

involved an online safety climate questionnaire on the issue. Obtained results have assured the lower perceptions of safety within organizations and for certified seafarers. That was mainly due to the extensive restrictions and the excessive maritime safety education and training seafarers often undergo. To determine the effect of different individual and occupational factors on psychological well-being and job satisfaction among merchant seafarers. McVeigh et al., (2019) conducted secondary data analysis administered by a large shipping company to seafarers. Based on the study, supportive, equal, and just-work environment was assured to be the foremost factor upon which the psychological well-being of seafarers primarily depends.

Grimm et al., (2020) investigated the interrelationship between cohesion, authentic leadership, and psychological safety in the maritime industry. The quantitative research has shown that authentic leadership is a crucial indication of psychological safety in the maritime industry. Further, the study ascertained the strong connection between psychological security and high-quality interpersonal relationships as well as effective leadership. Rahmoun & Said Essa, (2022) introduced an analysis for the possibility of integrating psychological security into safety critical operations, bridge teamwork as well as the requirements for seafarers. Comparing the application of psychological safety in different security critical domains with the Bridge Resource Management (BRM) required by STCW, the study recommended the practice of psychological safety practically for improving BRM training. Brooks & Greenberg, (2022) conducted a systematic survey concerning the essential factors closely intertwined with mental health and well-being in maritime personnel. They recommended boosting the wellbeing of maritime staff via improving mental health based on providing education, support as well as promoting crew members.

The quoted studies reflect on the importance of psychological security in the maritime industry broadly. Psychological security in the context of leadership and teamwork allies with relevant psychological theories, such as Maslow's Hierarchy of Needs (Maslow, 1943) and self-determination theory (Ryan & Deci, 2000). Grimm et al. (2020) advocate for the part played by leadership and cohesion, reiterating Maslow's assertion that social belongingness and security are basal human needs that help them perform professionally. Rahmoun & Said Essa (2022) also advocated for instilling psychological safety in safety-critical maritime operations, which is further explained in theories that suggest such types of detailed performance made by human beings when they function in an environment with wide-open communication and trust (Edmondson, 2018).

Moreover, Brooks & Greenberg (2022) talk about the relationship mentally between workplace well-being and mental health; the similarity emphasized by self-determination theory is autonomy, competence, and relatedness being motivational and satisfaction-laden aspects. Toward these lines, one can take psychological security not just a consequence of the conducive conditions as it happens to be a determining activity along with safety culture and productivity effectiveness in maritime environments.

The present study builds on these theoretical foundations through a broader perspective towards demographic and work-related factors influencing psychological security. Previous research has

indeed looked into psychological safety in leadership and operational contexts, but the current research takes this deeper into the environmental influences-family, colleagues, and work conditions to develop a very holistic understanding of seafarers' psychological security. This will be the foundation for any worthwhile improvement concerning seafarers' general well-being and the safety culture of the overall industry.

Upon reviewing the existing literature, it becomes evident that there is a notable scarcity of studies specifically addressing the issue of psychological security among seafarers. This does not, however, diminish the interest of researchers in this topic across various fields outside of maritime studies. By fostering an environment that supports the psychological security of seafarers, we create a workspace that encourages openness, tolerates mistakes, and promotes their acknowledgment without fear or hesitation. This not only benefits the seafarers but also enhances the overall functioning of the ship.

As Edmondson (2018) highlighted, a psychologically safe work environment that allows team members to voice their thoughts openly enhances team efficiency and productivity while reducing errors. This ultimately results in significant gains for the organization. Despite these insights, there remains a gap in published research investigating the safety levels of seafarers. Therefore, it is apparent that in regard to the psychological security factor, there exists a scarcity of research studies that have concentrated on the matter with respect to seafarers.

Research objectives

From the literature review, it's clear that research addressing the psychological security of seafarers is scarce, despite its importance in reducing human error in the maritime field. This study represents an initial step in exploring this area, focusing on the analysis of three vital environments surrounding seafarers: family characteristics, work, and colleagues' environment. The primary objective was to identify factors within these environments that may influence psychological security and determine their significance.

Additionally, the study aimed to develop a new scale based on Maslow's S-I Inventory to achieve these research objectives and to uncover which of these environments would have the most substantial impact on explaining psychological security.

Methodology and Demographic Analysis

The methodology for this study was developed following an extensive review of literature on psychological security, with a particular focus on the seafaring context. This review guided the identification of three key environments - personal characteristics, family characteristics, and work and colleagues' environment - and their respective factors that may influence seafarers' psychological security.

Building on Maslow's dimensions and Maslow's S-I Inventory, we crafted a comprehensive scale tailored to the unique circumstances of seafarers' work. This scale prioritizes behavioural attitudes over self-report statements to minimize the impact of social desirability bias.

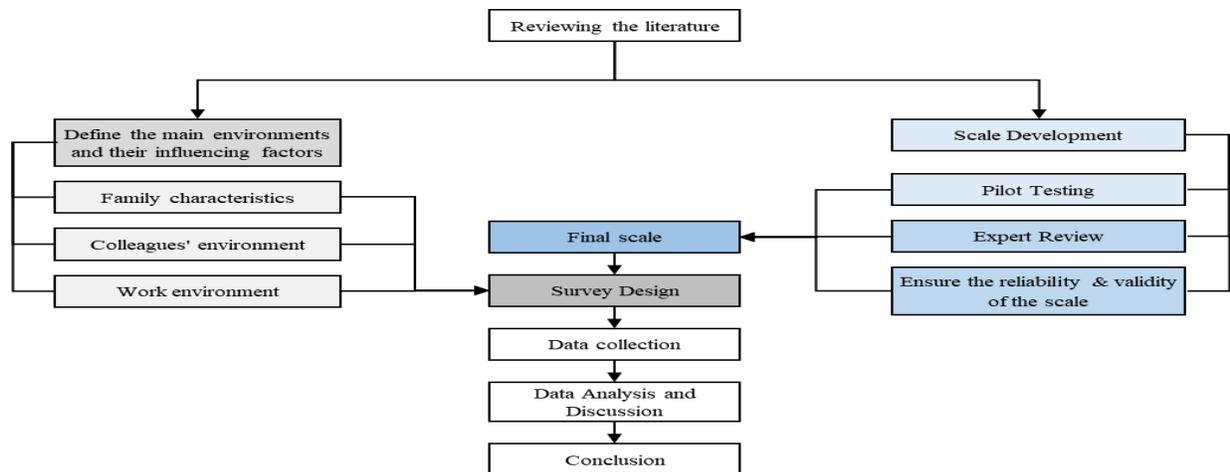


Figure 10: Methodology and Demographic Analysis research framework

The data collection method was through an online survey designed for the study sample as shared with different shipping and maritime unions and professional networks for maximum engagement to participate in the exercise. The survey was anonymous and had structured followed by open-ended questions directed at assessing psychologically secure seafarers comprehensively. A total of 248 completely responded surveys were obtained from Egyptian seafarers to create a dataset for further analysis. The sample consisted of seafarers with different ranks, types of vessels, and experience levels to ensure representivity from the workforce in the maritime industry.

The respondents represented seafarers working on different types of vessels. Of these, 48% were on offshore structures; 27% were on general cargo ships; 16% were bulk carriers and container ships, while 9% were on passenger ships. They include all aspects of maritime work-from captain, chief officer, and deck officer to engineer, electro-technical officer (ETO), and rating. The range of seafarer experience was also very broad-from less than three years to more than 20 years-in order to capture a good cross-section of the profession within the maritime industry.

Many participants were employed by both domestic and international shipping companies, enhancing the generalizability of the findings.

Under three major environments are classified the influences of psychological security:

- Family characteristics that comprised marital status, parenthood, and frequency of communication with family members
- Colleagues' environment: characterized by social interaction with crew members and the diversity of crew nationalities, and hierarchical relationships on board
- Work environment: type of vessel, food service quality, rest hours, nature of work, frequency of crew change, salary satisfaction, workout habits, and work area (deck vs. engine room).

Much of the previous research has focused on psychological safety in the leadership and operational environment; however, very few studies have dealt with the direct implications of the workplace on psychological security among seafarers. Given that maritime work is isolated and structured, factors such as crew dynamics, job satisfaction, rest hours, and recreational activities

are vital to understand the mental well-being and overall psychological security of seafarers. Our research, therefore, provides a systematic analysis of how these environmental factors contribute to psychological security and attempts to fill gaps in the existing literature.

This study, while investigating these environments alone, does not rule out the fact that there may be interactions between the two. More research can be built on this groundwork through moderation and mediation models like Structural Equation Modelling (SEM) to figure out how these aspects interact to affect seafarers' psychological security.

The participants were fully briefed on the nature and purpose of the study before the consent form was signed for participation. Figure 2 provides a model research framework to better understand the environmental effects on seafarers' psychological security.

Development of Psychological Security Scale (PSS) for seafarers:

Although different aspects of psychological security have been addressed by earlier researchers, we adopt the dimensions of Maslow and Maslow's S-I Inventory for this particular study. In this regard, the items of Maslow's Scale have been developed, and instead of self-report questions, we have been able to prepare a behaviourally anchored scale for clarity and consistency of responses. The intended variability in interpretation for each of the response options we piloted involving 20 seafarers with expert evaluators for further refinement of the wording toward accuracy. Coastwise psychologists further reviewed the scale to ensure its applicability and reliability in the seafaring setting.

The scale contains 30 behavioural attitudes, each of which has three distinct alternatives representing different levels of psychological safety. To illustrate, consider the attitude "Feeling secure," which corresponds to Attitude No. 7 in Table 1. The three alternatives speaking to this attitude would be: "Constant danger," "Unsafe in crises," and "Constantly secure," representing low, moderate, and high levels of psychological security, respectively, with the wording designed to correspond to realities as experienced by seafarers. This structured approach will allow an understanding of psychological security among seafarers without introducing considerable inconsistencies in interpretation of responses. The entire list of the attitudes and alternatives is represented in Table 1.

Table 1: Behavioural Attitudes for Psychological Security Scale for Seafarers

No.	Behavioural Attitude	Alternative 1	Alternative 2	Alternative 3
1	Response to Insult	High concern	Slight concern	Assured
2	Interaction during Rest	Non-interactive	Harmonious	Solitary
3	Teamwork Experience	Deeply friendly	Slightly friendly	Burdensome
4	Future Work Prospects	High concern	Slight worry	Secure
5	Boss Interaction	Little interest	Full attention	Unimportant
6	Joining New Ship	Highly accepted	Slightly accepted	Unaccepted
7	Feeling secure	Constant danger	Unsafe in crises	Constant secure

No.	Behavioural Attitude	Alternative 1	Alternative 2	Alternative 3
8	Crew Affiliation	Slight belonging	Strong belonging	No affiliation
9	Conflict Resolution	Highly understood	Slightly understood	Misunderstood
10	Handling Mistakes	High fear	Slight fear	Reassured
11	Crew Relationships	Superficial	Good	Bad
12	Reaction to Failure	Optimistic	Accepting	Self-pity
13	Social Dynamics	Constant threat	Fluctuating	Safe
14	Staff Discussions	Marginalized	Important	Stranger
15	Opinion Reception	Highly liked	Disliked	Mocked
16	Solitude on Ship	Unjustified fear	Slight fear	Reassured
17	Collaborative Tasks	Uncomfortable	Harmonious	Solitary
18	Urgent request refused	Sympathetic	Slightly upset	Hated
19	Long-term Onboard	Unlimited pressure	Bearable pressure	Comfortable
20	Emergency Response	Slight support	Full support	Medical help
21	Personal Crisis Response	Huge sympathy	Slight sympathy	No sympathy
22	Crisis Management	Panicked	Fearful	Reassuring
23	Colleague's Health Issue	Indifferent	Missed	Wished departure
24	Caring for colleagues	Enough attention	A little attention	Careless
25	Piracy Incident	Panicked	Fearful	Reassuring
26	Hearing Negative Gossip	Annoyed, passive	Annoyed, active	Indifferent
27	Delivering Bad News	Gradual, supportive	Gentle	Indifferent
28	Harassment Incident	Fearful, escapist	Fearful, self-protective	Anxious, self-protective
29	Multinational Crew	Incompatible	Understanding	Racialized
30	Bullying Experience	Upset, resilient	Ridiculed by one	Ridiculed by all

The behavioural attitudes are grouped into three scale dimensions: the need for safety, the need to belong, and the need for affection. These dimensions are derived from Maslow's hierarchy of needs and are central to our understanding of psychological security among seafarers. The behavioural attitudes are varying between receiving or providing love, security and belonging, the distribution of scores among the alternatives of attitudes and their corresponding scale dimensions are presented in Table 2.

Table 2: Distribution of Scores Among the Alternatives of Attitudes and Corresponding Scale Dimensions

Scale dimensions	Attitudes number	Distribution of scores among the alternatives of Attitudes
The need for safety	1- 4- 7- 10- 13- 16- 19- 22- 25- 28	1- 2- 3
The need to belong	2- 5- 8- 11- 14- 17- 20- 23- 26- 29	2- 3- 1
The need for affection	3- 6- 9- 12- 15- 18- 21- 24- 27- 30	3- 2- 1

The total scores of the scale are calculated from the sum of scores on 30 behavioural attitudes, with the maximum possible score being 90 and the lowest one being 30. A high total score indicates high psychological security and vice versa. The distribution of scores on behavioural attitudes' alternatives are shown in Table.

Table 3: Numerical rating for alternatives of Attitudes

Numerical rating	Verbal judgement of alternatives of Attitudes
1	The Lowest level of psychological security
2	An average level of psychological security
3	The highest level of psychological security

In addition to the 30 behavioural attitudes, the scale also includes socio-demographic questions about various aspects of the seafarers' personal and professional life. The scale was evaluated and verified rigorously through pilot testing before the final survey was developed. This process involved feedback from 20 seafarers and a group of academic experts, which was used to refine the questions and develop the final scale.

Validity and reliability of the developed Psychological Security Scale:

Cronbach's alpha coefficient, often denoted as " α ", is a widely used statistical measure to determine the internal consistency or reliability of a test or scale. It provides a measure of how well the items in a set are positively correlated to one another. The coefficient values range between 0 and 1, with values closer to 1 indicating higher reliability. Typically, an alpha of 0.7 or above is considered acceptable, though this can vary depending on the field of study (Tavakol & Dennick, 2011).

For the Psychological Security Scale tailored for seafarers, the Cronbach's α coefficient was utilized to evaluate the scale's reliability. The derived Cronbach's α value was 0.788, indicating satisfactory overall reliability. Further scrutiny revealed that excluding any item, barring item (28), would decrease the scale's reliability. Omitting item (28) adjusted the Cronbach's α coefficient to 0.792, leading to its removal and retaining 29 behavioural attitudes in the scale.

Items numbered (9, 11, 12, 23, 25, 26) were discerned as low-discrimination items, having a discrimination value below 0.2, and were thus excluded, resulting in a set of 23 behavioural

attitudes. An extreme group test, involving the top and bottom 27% of total scores, was executed. An independent sample t-test applied to these groups yielded a significance of $P= 0.01$, indicating the scale's efficacy in distinguishing between varying levels of psychological security. The scale's validity was further verified using Confirmatory Factor Analysis, with the results tabulated in Table 2.

Table 2: Confirmatory Factor Analysis results

Model	X2	df	P	GFI	AGFI	CFI	NFI	TLI	IFI	RMSEA
Psychological security	3.587	2	.166	.990	.971	.991	.980	.987	.991	.057
Assessment	Great			Great	Great	Great	Great	Great	Great	Good

The fit results for the psychological security model were exemplary. The P value for X2 indicates the model's goodness of fit, with a non-significant value suggesting a good fit. GFI (Goodness of Fit Index), AGFI (Adjusted Goodness of Fit Index), CFI (Comparative Fit Index), NFI (Normed Fit Index), TLI (Tucker-Lewis Index), and IFI (Incremental Fit Index) are fit indices, with values closer to 1 indicating a better fit. The RMSEA (Root Mean Square Error of Approximation) value measures the model's error, with values below 0.1 indicating a good fit. These metrics collectively suggest that the data aligns well with the proposed model.

Moreover, the standardized path diagram is provided in Figure 11. the statistical outcomes affirm the successful development of a novel measure of psychological security rooted in Maslow's theory. This measure emphasizes behavioural attitudes over self-reporting and is tailored to the unique nature of seafarers' work. After rigorous reliability and validity checks, the finalized scale comprises 23 behavioural attitudes to gauge psychological security among seafarers Appendix 2.

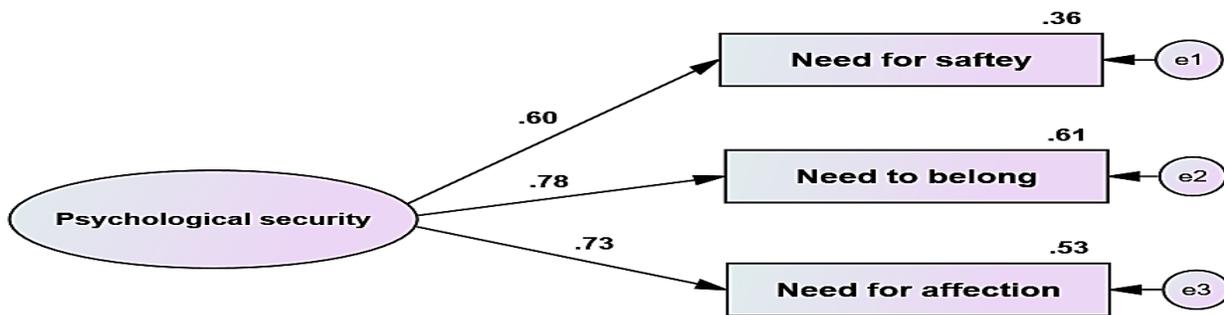


Figure 11: standardized path diagram for psychological security model.

Results

Statistical Analysis

All computations were carried out using SPSS V.28. To examine for differences in psychological security, Independent-Sample T-Tests were used for comparisons between two independent groups, for example, gender and the absence or presence of chronic disease. Comparisons of three or more groups were done using One-Way Analysis of Variance (One-Way ANOVA) to determine significant differences among several categorical variables such as age groups, levels of

experience, and types of vessels. In addition, a Hierarchical Multiple Regression was used to analyze the proportion of the variance (R^2) in psychological security accounted for by family-related variables, colleagues' environment, and work environment variables. This multi-level process ensured that both direct effects and total accumulation contributions of the predictor variables were assessed systematically.

Associations between Demographic Characteristics and Psychological Security

The study encompassed 248 Egyptian seafarers, representing a diverse range of positions, experience levels, and vessel types. A detailed breakdown of the seafarers' characteristics can be found in Appendix 1. To discern differences across variable groups, Independent-sample t-tests and ANOVA were utilized. The findings, as presented at Table 3 revealed significant disparities in psychological security among seafarers based on several factors: communication with family ($t= 9.469, P<.001$), intra-crew social communication ($t= 6.084, P= .003$), crew nationality ($t= 1.858, P= .032$), work area ($t= 2.717, P= .004$), quality of food service ($t=17.599, P<.001$), rest periods ($t= 8.674, P<.001$), adherence to crew change schedules ($t=2.020, P= .022$), satisfaction with salary ($t= 3.712, P<.001$), and engagement in workouts ($t=5.052, P<.001$).

Table 3:Demographic variables by psychological security (n=248)

Variable	n	Mean	SD	T/ F	P- value
Age	less than 30 years	46	60.42	1.894	.131
	30- 40 years	133	59.15		
	40- 50 years	60	60.89		
	more than 50 years	9	60.51		
Gender	Males	238	59.85	.084	.466
	Females	10	59.99		
Years of experience	less than 3 years	24	58.63	1.661	.176
	3- 9 years	87	59.20		
	9- 15 years	57	60.71		
	more than 15 years	80	60.32		
Academic study	Vocational	119	60.55	2.704	.069
	Bachelor	111	59.40		
	Postgraduate	18	58.02		
Suffering from diseases	Yes	10	59.91	.036	.485
	No	238	59.85		
Marital status	Married	187	59.76	.481	.619
	Single	58	60.27		
	Divorced	3	57.71		
Having kids	Yes	174	59.86	.011	.495
	No	74	59.85		
Communication level with	Weak	28	56.33	9.469	<.001
	Moderate	165	59.96		

Variable		n	Mean	SD	T/ F	P- value
family	Strong	55	61.33	4.491		
	Weak	120	58.99	5.160		
communication between crew	Moderate	11	57.29	7.062	6.084	.003***
	Strong	117	60.98	4.710		
Crew nationality	Same nationalities	77	60.75	5.154	1.858	.032**
	Different nationalities	171	59.45	5.111		
Position	Captains	29	59.35	5.584		
	Chief officer	17	58.25	5.286		
	Second officer	31	59.01	6.603		
	Third officer	8	55.46	8.106	1.878	.074
	Chief engineer	11	59.54	4.383		
	Second engineer	42	60.00	5.214		
	Third engineer	89	60.97	3.893		
Work area	ETO	21	59.93	4.908		
	Deck crew	85	58.64	6.163	2.717	.004***
	Engine room	163	60.49	4.423		
Type of vessel	offshore	120	59.94	5.223		
	general cargo	66	59.72	5.514	.174	.914
	bulk- RoRo- container	39	60.16	4.173		
	Passengers	23	59.26	5.443		
Food service	Good	175	60.97	4.623		
	Moderate	63	57.58	5.004	17.599	<.001
	Bad	10	54.58	7.121		
Rest hours	More than 12 hours	36	61.88	3.354		
	12 hours	133	60.36	4.985	8.674	<.001
	Less than 12 hours	79	58.07	5.598		
Work nature	Physical work	35	61.56	4.211		
	Paperwork	10	59.38	5.440	2.262	.106
	Both	203	59.58	5.248		
scheduled crew change	Yes	159	60.35	4.965	2.020	.022**
	No	89	58.98	5.382		
Salary satisfaction	Yes	150	60.81	4.275	3.712	<.001
	No	98	58.39	5.990		
Doing workouts	Yes	126	61.40	3.654	5.052	<.001
	No	122	58.25	5.938		

Results point out that there are differences in the level of psychological security due to the level of communication between the family in Favor of those with strong communication with their families (M= 61.33 / SD= 4.491) and there are differences due to the level of communication

between crew in favour of those with the strong communication ($M= 60.98 / SD= 4.710$) as detailed in Table 3 and Figure 12.

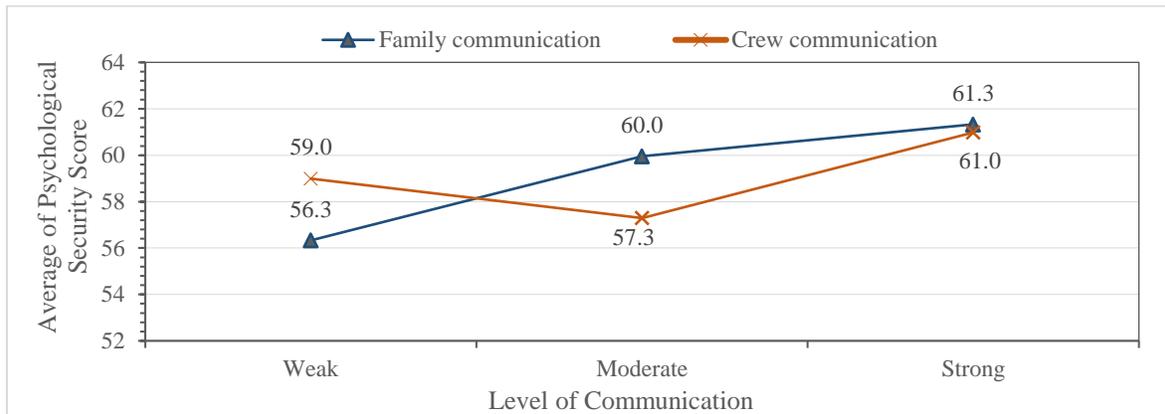


Figure 12: Average Psychological Security Score according to family and crew level of communication

Also, the result showed that there are differences according to food service in favour of those who have a good food service ($M= 60.97/ SD= 4.623$), and there are differences according to rest hours in favour of those who have more than 12 hours for rest ($M= 61.88/ SD= 3.354$) Table 3 & Figure 13. We can also see that there are differences according to crew nationality in favour of those who have worked with crew from the same nationality ($M= 60.75, SD= 5.154$), Also, seafarers who worked at engine room have a high level of psychological security than deck crew ($M= 60.49, SD= 58.64$) Table 3 & Figure 14. Result emphasized that there are differences between Egyptian seafarers due to crew change, salary satisfaction and doing workouts in favour of who have scheduled crew change, are satisfied about salary, and did workouts. Respectively ($M= 60.35, 60.81, 61.40$), ($SD= 4.965, 4.275, 3.654$) Table 3 & Figure 15.

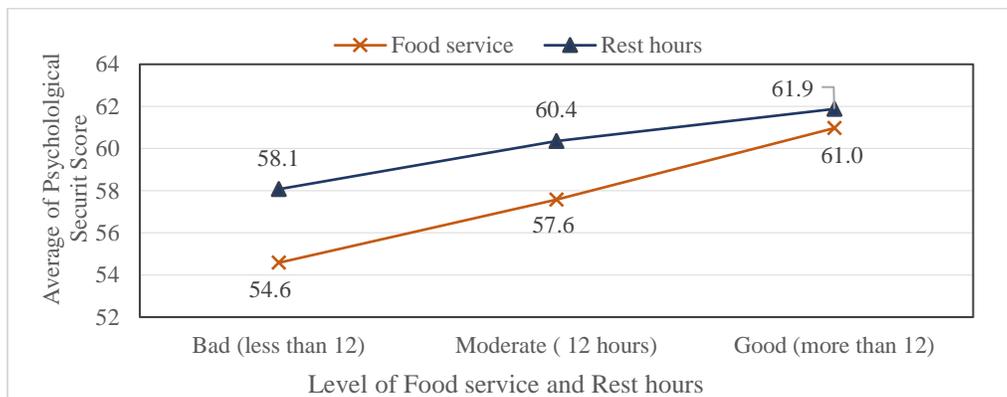


Figure 13: Psychological Security Score according to food service quality and rest hours

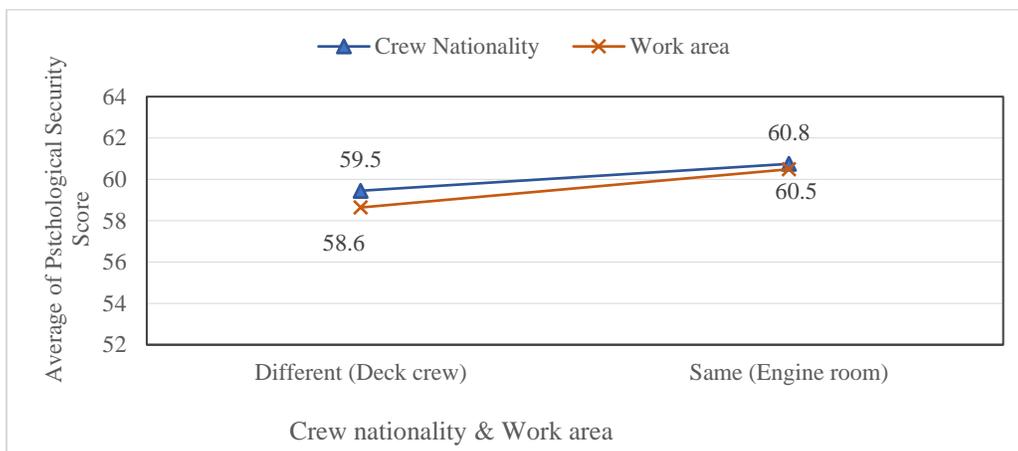


Figure 14: Psychological Security Score according to crew nationality & work area.

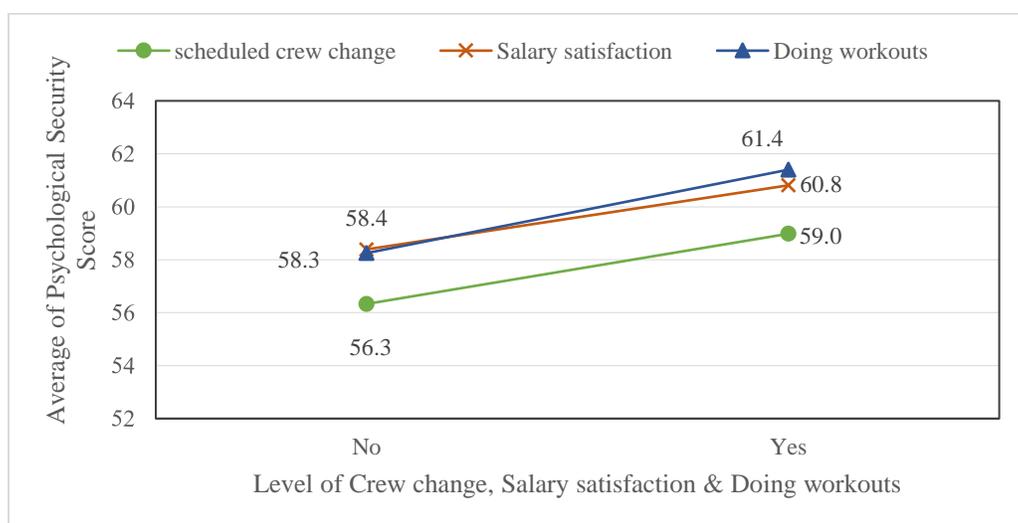


Figure 15: Psychological Security Score according to crew change, salary satisfaction and doing workouts.

Hierarchical multiple regression Models

Hierarchical multiple regression explored how much of the variance in psychological security among seafarers could be accounted for by demographic variables in 3 main fields (family characteristics, colleagues' environment and work environment). Because all the demographic variables in this study are nominal variables, we set it as a dummy variable to ensure the accuracy of analysis. In model one (step 1), the significant demographic factors from family characteristics added as a predictor included (communication level with family). The second model consisted of the variables in Model 1, plus colleagues' environment. Significant factors added as a predictor included (social communication between crew and crew nationality). The third model consisted of the variables in Model 1, 2 plus significant work environment. Factors were entered as predictors which included (work area, food service, rest hours, scheduled crew change, salary satisfaction and doing workouts).

Table 4: Hierarchical multiple regression analysis for demographic variables in predicting psychological security (n = 248).

Variable	Model 1 (family characteristics)			Model 2 (colleagues' environment)			Model 3 (work environment)			
	B	SE	B	B	SE	β	B	SE	β	
communication with family	Strong	5.004***	1.157	.404	4.353***	1.178	.352	1.944	1.163	.157
	moderate	3.632***	1.018	.333	3.584***	1.007	.329	1.790	.983	.164
	Weak (ref)									
social communication between crew	Strong				1.582**	.669	.154	.676*	.638	.066
	moderate				-.840	1.560	-.034	-.613	1.451	-.025
	Weak (ref)									
crew nationality	Same nationality				1.233	.679	.111	1.831***	.642	.165
	Different nationalities (ref)									
work area	Engine room							1.791***	.622	.165
	Deck crew (ref)									
food service	Good							4.050*	1.581	.359
	moderate							2.187	1.592	.185
	Bad (ref)									
rest hours	>12 hours							.897*	.677	.087
	12 hours							1.938	.956	.133
	< 12 hours (ref)									
scheduled crew change	Yes							.324	.627	.030
	No (ref)									
salary satisfaction	Yes							.709	.636	.067
	No (ref)									
doing workouts	Yes							2.026***	.633	.197
	No (ref)									
Constant		56.333			55.417			50.359		
R2		.072			.112			.277		
Adjusted R2		.064			.094			.236		
F/ P- value		9.469/ <.001			6.107/ <.001			6.885/ <.001		

Hierarchical multiple regression results showed that work environment factors combined with colleagues' environment explained 28% of the variance ($R^2 = .277$, $p < .001$) in psychological security, while colleagues' environment combined with family characteristics explained 11% of the variance ($R^2 = .112$, $p < .001$), and only family characteristics explained 7% of the variance ($R^2 = .072$, $p < .001$) in psychological security Table 4 & Figure 16

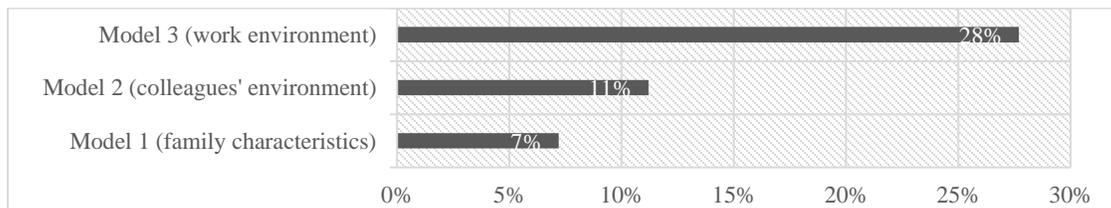


Figure 16: Variance percentage in psychological security according to the three models

In model one, all predictors were statistically significant, compared to seafarers who have weak communication with family. Those who have strong/ moderate communication reported significant psychological security ($B = 5.004$ / $B = 3.632$, $p < .001$) Table 4. This indicates that an increase by one unit in the level of communication with family leads to an increase in the psychological security rate of seafarers by a rate of (5) units. In model two, all predictors were statistically significant except crew nationalities, compared to seafarers who have weak social communication between crew. Those who have strong social communication reported significant psychological security ($B = 1.582$, $p < .001$), while the B coefficient for those who have moderate social communication did not reach conventional levels of statistical significance ($B = -.840$, $p = 0.722$) Table 4. This indicates that an increase by one unit in the level of strong social communication between crew leads to an increase in the psychological security rate of seafarers by a rate of (1.6) units. In model three, all predictors were statistically significant except scheduled crew change and salary satisfaction, Model 3 also showed that crew nationality was added while the relationship of family's communication with psychological security was eliminated when work environment's factors are included in the model, suggesting that the variance in psychological security is better explained by work environment's and colleague's factors together than family characteristics as it one.

By looking at model three, compared with seafarers who worked at deck crew, those who have worked at engine room reported significant psychological security ($B = 1.791$, $p < .001$). Compared with seafarers who have bad food service, seafarers who have good food service reported significant psychological security ($B = 4.050$, $p < .05$), while the B coefficient for those who have moderate food service did not reach conventional levels of statistical significance ($B = 2.187$, $p = 0.171$). This indicates that an increase by one unit in the level of good food service leads to an increase in the psychological security rate of seafarers by a rate of (4) units. Also, compared with seafarers who have less than 12 hours for rest, seafarers who took more than 12 hours reported significant psychological security ($B = .897$, $p < .05$), while the B coefficient for those who have 12 hours did not reach conventional levels of statistical significance ($B = 1.938$, $p = 0.186$). This indicates that an increase by one unit in the level of rest hours (more than 12 hours) leads to an

increase in the psychological security rate of seafarers by a rate of (.90) units. Finally, by comparing, seafarers who did not do workouts, those who did it ($B = 2.026, p < .001$), This indicates that an increase by one unit in the level of workouts leads to an increase in the psychological security rate of seafarers by a rate of (2) units Table 4.

Discussion

To the best of the authors' knowledge, this is the first study addressing seafarers' psychological security in a quantified manner. The developed scale was applied to a group of Egyptian seafarers to validate it. In this context, the study explored the level of psychological security, examining the influence of personal, family characteristics, colleagues', and work environment factors. Through hierarchical regression analysis, significant contributors were identified among this specific group, such as communication with family, social interaction among crew, crew nationality, work area, food service, rest hours, and participation in workouts as shown in Table 4. The results revealed that work and colleagues' environment factors collectively explained 28% of the variance in psychological security, as detailed in Figure 16. & Table 4 Interestingly, within this context, the importance of family communication as a predictor diminished when factors related to work conditions were introduced into the model. This insight suggests that enhancing social communication among seafarers and improving work conditions could meaningfully increase their level of psychological security. The study thus offers a nuanced understanding of psychological security among Egyptian seafarers and highlights the integral role of work and social environments in shaping it.

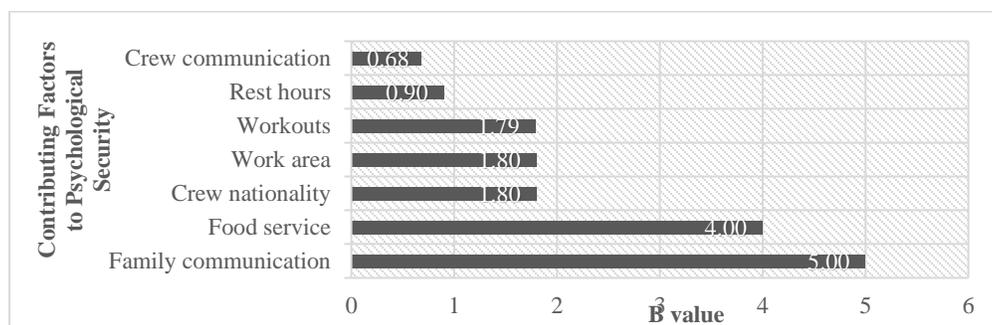


Figure 17: Statistically significant contributing factors to psychological security.

This result seems logical to a large extent, as the surrounding conditions are greatly reflected on the psychological aspect of the individual. So, whenever the working conditions are appropriate and satisfactory to the seafarer, this is reflected in his sense of psychological security and psychological well-being in general and on his performance at work. Also, social communication supports the individual's sense of belonging to the individuals with whom he works and to the place in which he works, considering that the working conditions of seafarers make them spend a long time on the ship, which may be much more than the period they spend with their families. This explains why the work environment and colleagues gain greater importance in interpreting psychological security when linked to communication with the family.

Egyptian Seafarers in this study achieved a moderate level of psychological security regarding to the higher level of psychological security among our participants, who have good food service, have more than 12 hours for rest Table 3 & Figure 13. Also, those who have a scheduled crew change, have a satisfaction for salary and doing workouts as an activity, Table 3 & Figure 15. That is agreed with the main purpose of Maslow (1943b) theory of needs, he Emphasize the importance of meeting physiological needs first including having enough food, sleep, so that the individual can think of higher needs and satisfy them such as need for security. Also, Taormina & Gao (2013) pointed out that meeting the physiological needs of the individuals enables them to feel secure and magnifying the feeling of emotional/psychological security. And as Taormina & Sun (2015) mentioned “The more Physiological Needs Satisfaction people have, the less Psychological Insecurity they will have”.

the International Committee on Seafarer’s Welfare, in the Seafarer’s Health Information Programme, sponsored by the ITF Seafarer’s Trust referred to some guidelines for mental care onboard Ships which included the quality of rest periods, adequate time for uninterrupted rest and leisure activities on-board as cited in (Menon, 2011)

Current results point us to that seafarers who have strong communication with their families have a higher level of psychological security than others and seafarers who have strong social communication with their crew have a higher level of psychological security than Table 3 & Figure 12 and that is in line with Maslow et al.(1945b) who emphasized that receiving support from co-workers helps reduce feelings of insecurity, referring to the importance of the role of colleagues in achieving a high level of psychological security. Despite the harsh working conditions inside the engine room, they showed a high level of psychological security Table 3 & Figure 14 compared to deck crew. we suggest that the reason for that is most of participants in this study are working at offshore structure in which the big load is on the deck crew while the engine room is auxiliary machinery. Seafarers who worked with crew from the same nationality reported a high level of psychological security Table 3 & Figure 14. We attribute this to the fact that working with people from the same nationalities makes the seafarer feel at home and enrich the feeling of belonging which reduces the impact of the long time he spends at sea and reduces the alienation felt by seafarer.

The findings of this study, while insightful, are subject to certain limitations. The reliance on a sample of Egyptian seafarers may restrict the generalizability of the results to other populations. Despite efforts to include a diverse sample, the gender imbalance and specific characteristics of the sample may have influenced the findings. Additionally, while the study identified three main environments affecting psychological security, other factors and environments may exist that were not explored in this research.

However, it's essential to recognize that the primary objective of this study was to validate the newly developed scale for assessing psychological security among seafarers. The methodology and the novel scale have shown promise, and the authors are confident that with more diverse and extensive data, more generalized results can be obtained. Future research should consider

employing mixed methodologies for in-depth analysis and expanding the sample to different nationalities and characteristics.

These limitations do not diminish the study's contributions but rather guide future research directions. The study serves as a preliminary step in a vital area that has not been extensively explored, laying the groundwork for further investigation and refinement of the methodology.

Conclusion

This research offers insights into the psychological security of seafarers, with a particular focus on Egyptian seafarers. The findings underscore the significance of colleagues' and work environment factors as key determinants of psychological security. Furthermore, the study validates the newly developed psychological security scale as an effective tool for assessing seafarers' mental well-being.

Given the pivotal role of psychological security in maritime work, future research should delve into strategies for bolstering seafarers' psychological resilience, especially during challenging periods onboard. Investigating the psychological aftermath of maritime incidents could also be enlightening. Expanding this line of inquiry to diverse samples and exploring its interplay with other maritime-related variables would further enrich our understanding.

The study advocates for the integration of psychological assessments in seafarers' training programs, given their profound impact on maritime performance. Periodic monitoring of seafarers' mental health and consistent psychological support are also recommended.

In sum, the psychological security of Egyptian seafarers warrants significant attention. While the findings are illuminating, the specific characteristics of the sample used necessitate caution in generalizing the results. Broader applications to varied samples are likely to yield more encompassing insights. The study also suggests a more granular exploration of the three studied environments, possibly integrating mixed methodologies. Notably, there remains a gap in literature concerning seafarers' psychological security, presenting ample opportunities for further research.

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Appendix 1: characteristics of participants:

Variable		Category	N (%)	Variable	Category	N (%)
Personal characteristics	Age	less than 30 years	46 (18.5 %)	Years of experience	less than 3 years	24 (9.7 %)
		30- 40 years	133 (53.6 %)		3- 9 years	87 (35.1 %)
		40- 50 years	60 (24.2 %)		9- 15 years	57 (23 %)
		more than 50 years	9 (3.6 %)		more than 15 years	80 (32.2 %)
	Gender	Males	238 (96 %)	Suffering from diseases	Yes	10 (4 %)
		Females	10 (4 %)		No	238 (96 %)
	Academic study	high School (precollege)	119 (48 %)	Communication level with family	Weak	28 (11.3 %)
		Bachelor's	111 (44.2 %)			
		Master's/ Ph.D. (postgraduate)	18 (7.3 %)			
	Family characteristics	Marital status	Married	187 (75.4 %)	Communication level with family	moderate
Single			58 (23.4 %)			
Divorced			3 (1.2 %)			
Having kids		Yes	174 (70.2 %)	Strong		55 (22.2 %)
	No	74 (29.8 %)				
colleagues Environment	Social communication between crew	Weak	120 (48.4 %)	Position	Chief engineer	11 (4.4 %)
		Moderate	11 (4.4 %)			
		Strong	117 (47.2 %)			
	Crew nationality	Same nationalities	77 (31 %)			
		Different nationalities	171 (69 %)			
	Position	Captains	29 (11,7 %)		Second engineer	42 (16.9 %)
Chief officer		17 (6.9 %)				
	Second officer	31 (12.5 %)	Third	89 (35.9 %)		

Variable	Category	N (%)	Variable	Category	N (%)	
Work Environment	Third officer	8 (3.2 %)	engineer		%	
	ETOs	21 (8.5 %)	ETO			
	offshore structure or vessel	120 (48.4 %)	Good		175 (70.6 %)	
	Type of vessel	general cargo	66 (26.6 %)	Food service	moderate	63 (25.4 %)
		bulk- RoRo- container	39 (15.7 %)		Bad	10 (4 %)
		Passengers	23 (9.3 %)		Physical work	35 (14.1 %)
		More than 12 hours	36 (14.5 %)		Paperwork	10 (4 %)
	Rest hours	12 hours	133 (53.6 %)	Work nature	Both	203 (81.9 %)
		Less than 12 hours	79 (31.9 %)		Yes	126 (50.8 %)
	Existence of scheduled crew change	Yes	159 (64.1 %)	Doing workouts	No	122 (49.2 %)
	No	89 (35.9 %)		Deck crew	85 (34.3 %)	
Salary satisfaction	Yes	150 (60.5 %)	Work area	Engine room	163 (65.7 %)	
	No	98 (39.5 %)				

Appendix 2: psychological security scale:

	Behavioural Attitudes	Scale dimensions	Distribution of scores
Response to Insult	If you were insulted by a colleague on board...		
	I am very concerned that this could happen again.	need for safety	1- 2- 3
	I am slightly concerned that this might happen again.		
	Rest assured that this will not happen again.		
Interaction during Rest	When the rest time comes after working hours...	need to belong	2- 3- 1
	I sit with my colleagues but do not interact		

	Behavioural Attitudes	Scale dimensions	Distribution of scores
	with them. I sit with my colleagues in harmony with them. I prefer to sit alone because I feel alienated.		
Teamwork Experience	When you work in a team... I feel deeply friendly by others. I feel a little friendly from others. I feel like a burden to others.	need for affection	3- 2- 1
Future Work Prospects	When you think about the nature of your work... I am very concerned about my future. I have a slight worry about my future. I feel secure about my future.	need for safety	1- 2- 3
Boss Interaction	While talking to your boss... I feel little interest from him. I feel complete attention from him. I feel like an unimportant member of the team.	need to belong	2- 3- 1
Joining New Ship	When you join a new ship for the first time... I feel very accepted by the crew. I feel a little accepted by them. I feel unaccepted.	need for affection	3- 2- 1
Feeling secure	While on board the ship... I feel like my life is in danger all the time. I feel dangerous only when in critical situations. I feel constantly safe while at work.	need for safety	1- 2- 3
Crew Affiliation	With reference to teamwork among your ship's crew... I feel a little bit of a sense of belonging towards them. I feel a huge sense of belonging to my crew. I have no affiliation with this crew.	need to belong	2- 3- 1

	Behavioural Attitudes	Scale dimensions	Distribution of scores
Handling Mistakes	<p>If you make an unintentional mistake in your work...</p> <p>I am very afraid of what will happen to me.</p> <p>I have a slight fear of the consequences of things.</p> <p>I feel reassured that I will take my right as it should</p>	need for safety	1- 2- 3
Social Dynamics	<p>when you deal with others...</p> <p>I feel threatened all the time by them.</p> <p>My feelings fluctuate between threat and reassurance.</p> <p>I feel safe when dealing with them.</p>	need for safety	1- 2- 3
Staff Discussions	<p>When you discuss with your staff about a topic...</p> <p>I feel marginalized by them.</p> <p>I feel like an important part of the team.</p> <p>I feel like a stranger to them.</p>	need to belong	2- 3- 1
Opinion Reception	<p>When you express your opinions to those around you...</p> <p>I feel they like my opinions very much.</p> <p>I feel like they didn't like my views.</p> <p>I feel they are making fun of my views.</p>	need for affection	3- 2- 1
Solitude on Ship	<p>If you are alone in one of the places on the ship...</p> <p>I feel very unjustified fear.</p> <p>I feel a slight fear.</p> <p>I feel reassured.</p>	need for safety	1- 2- 3
Collaborative Tasks	<p>If you are asked to perform a task in collaboration with another colleague....</p> <p>I was forced to accept, not feeling comfortable.</p> <p>I accept because I get along easily with others.</p> <p>I refuse, preferring to work alone.</p>	need to belong	2- 3- 1
Urgent request refused	<p>your boss refused to give you a much-needed vacation...</p> <p>I feel his sympathy, trying to understand his attitude.</p>	need for affection	3- 2- 1

	Behavioural Attitudes	Scale dimensions	Distribution of scores
	I only feel bad for a little while. I feel like I'm being hated, taking bad action.		
Long-term Onboard	When you are on board the ship for a long time..... I feel unlimited pressure. I feel bearable pressure. I feel comfortable all time.	need for safety	1- 2- 3
Emergency Response	If a difficult situation happens to you on board the ship such as (accident- injury- illness) ... I get simple support from just some. I get fully support from everyone. I only get help from medical staff.	need to belong	2- 3- 1
Personal Crisis Response	You heard the news of death/ illness one of your relatives while you were on board the ship... I find huge sympathy from my crew. I find little sympathy with me. I find no sympathy from those around me.	need for affection	3- 2- 1
Crisis Management	22 If an emergency case occurred on board, such as (Fire- Flooding- Pollution- Collision), and you find your crew panicking... I feel very panicked with them, which makes it worse. I am overcome with fear, and it is difficult for me to try to calm them down. I show calm to my crew, spreading reassurance among them.	need for safety	1- 2- 3
Caring for colleagues	If you find a member of your crew introverted... I'm giving him enough attention to get over it. I'm trying to give him a little bit of attention. I don't care about him, even if his condition gets worse	need for affection	3- 2- 1
Delivering Bad News	If you are tasked with communicating a bad decision to your crew members... Tell them gradually while providing them	need for affection	3- 2- 1

	Behavioural Attitudes	Scale dimensions	Distribution of scores
	<p>with all the necessary support. Just tell them in a nice way to make things easier for them. Tell them without caring about their feelings.</p>		
Multinational Crew	<p>If you work with a crew consisting of different nationalities... I feel incompatible with them. I feel a good understanding with them. I feel racialized by them all the time.</p>	need to belong	2- 3- 1
Bullying Experience	<p>If you have been bullied by a member of your crew... I feel upset, but I don't let it affect me. I just feel like I'm being ridiculed by this person. I feel ridiculed by all the crew.</p>	need for affection	3- 2- 1

Bridging the Gap: Modernizing Environmental Management Systems in Egyptian Seaports to Align with Global Maritime Transport Trends

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المستخلص

إن ابتكار وتحديث أنظمة الإدارة البيئية (EMS) في الموانئ المصرية ضرورة حتمية تسير بالتوازي مع الإتجاهات الدولية نحو الإستدامة البحرية وتعزيز القدرة التنافسية، وذلك في ظل تشديد السياسات العالمية في هذا القطاع. تستند هذه الدراسة إلى تطبيق تحليل نقاط القوة والضعف والفرص والتهديدات (SWOT) ودراسات مقارنة لحالات موانئ عالمية رائدة (روتterdam، سنغافورة، لوس أنجلوس) بهدف تحديد القضايا الجوهرية في نظم الإدارة البيئية بالموانئ المصرية.

تشير النتائج إلى وجود فجوات تكنولوجية (الانتقال من تقارير الإنبعاثات التقليدية بشكلها المعتاد إلى أنظمة المراقبة بالذكاء الاصطناعي وتقنيات البلوك تشين)، وفجوات تنظيمية (تعارض الأطر القانونية الحالية مع أحدث تعديلات أحكام الملحق السادس لإتفاقية ماربول و إستراتيجية المنظمة البحرية الدولية للغازات الدفيئة والإنبعاثات الكربونية)، وفجوات تمويلية (نطاق التمويل الأخضر)، وفجوات محلية (عدم إستغلال إمكانيات الطاقة الشمسية بالشكل الأمثل وكذلك الأمور الخاصة بمعالجة قضايا التنوع البيولوجي)، وتعرض الدراسة لإجراءات محددة، منها مقترحات لتبني إستراتيجيات خفض الكربون بنسبة 40% بحلول 2030 و 70% بحلول 2050، ودمج المرافق المينائية الخاصة بتزويد السفن بالطاقة، وإنشاء صناديق مناخ وطنية لدعم إستثمارات الموانئ وجذب الإستثمارات الأجنبية.

تسعى هذه الإستراتيجيات إلى الإستفادة من الموقع الجغرافي لمصر ووجود قناة السويس كمر ملاحي عالمي بها وكذلك تعظيم الإستفادة من موارد طاقتها الشمسية، بهدف تحويل الموانئ المصرية إلى مراكز بيئية رائدة. وفيما يتعلق بإستدامة صناعة النقل البحري، تدمج هذه الدراسة بين النماذج النظرية والتطبيقات العملية، مقدمة دليلاً لصناع القرار ومديري الموانئ البحرية للإمتثال للمتطلبات الدولية ودعم رؤية مصر 2030 والإستراتيجية الوطنية للموانئ الخضراء 2030.

الكلمات المفتاحية: أنظمة الإدارة البيئية (EMS)، الإستدامة البحرية، تنافسية الموانئ، الموانئ الخضراء، رؤية مصر 2030.

Abstract

Innovation of Environmental Management Systems (EMS) at Egyptian seaports needs to be done in parallel with the international trends toward maritime sustainability and competitiveness due to stricter global policy within the industry. This research is based on implementing Strengths,

Weaknesses, Opportunities, and Threats (SWOT) analysis and comparative case studies of leading ports (Rotterdam, Singapore, Los Angeles) to determine the key issues of Egypt's Environmental Management System (EMS). The results indicate the presence of technological gaps (shifts from manual emissions reporting to AI monitoring and blockchain tracking), regulatory gaps (contradiction of the local legal frameworks with MARPOL Annex VI provisions), funding gaps (scope of green funding), and local gaps (non-uses of solar energy and addressing biodiversity conservation). The study outlines specific actions, including legislative changes for the adoption of carbon reduction strategies for 40% by 2030 and 70% by 2050, integration of shore power enabling facilities, and creation of supporting national port climate funds to invite foreign investment. The strategies seek to leverage Egypt's geographical location next to the Suez Canal and solar energy with the aim of changing Egyptian seaports into pro-environmental centers.

With regard to sustainability in maritime shipping, this study integrates models with real-world applications, providing a guide for decision-makers and port managers to meet international requirements while furthering Egypt's Vision 2030 and the National Strategy for Green Ports 2030.

Keywords: Environmental Management Systems (EMS), Maritime Sustainability, Port Competitiveness, Green Ports, Egypt's Vision 2030

1- Introduction:

Maritime transport aids in trade movement throughout the globe, accounting for over 80% of this trade by volume (UNCTAD,20233) The environmental pollution that stems from this sector, contributing 3% of greenhouse gases (GHG) emissions alongside marine pollution, showcases the urgent need for the modernization of port EMSs (Onyeabor, 2024). For countries like Egypt, whose maritime ports host pivotal trade arteries such as the Suez Canal and Mediterranean corridors, the need to align environmental management systems with global maritime trends is not only an ecological responsibility but also a vital necessity to remain competitive in light of stricter international regulations.

The International Maritime Organization (IMO) Revised GHG Strategy (2023) targets a 40% cut in shipping carbon intensity by 2030 and a 70% cut by 2050, which forces ports to implement innovations such as shore power supply, green hydrogen infrastructure, and AI emissions monitoring(Sarantopoulos, 2024). At the same time, the United Nations Sustainable Development Goals (SDGs), especially SDG 13 (Climate Action) and SDG 14 (Life Below Water), require ports to incorporate circular economy strategies and safeguard marine biodiversity(Caliskan, 2022). There is growing compliance through frameworks like the EU Emissions Trading System.

Regardless of these necessities, Egyptian seaports have to implement the new global standards. The Guidance Manual for Implementing EMS in Egyptian Seaports underscores systemic gaps:

- Technological shortcomings: Dependence on manual emissions reporting systems and fossil-fuel-based infrastructure, while other ports in the world, like Rotterdam port have AI-enabled air quality monitoring networks fully operational.

- Regulatory gaps: Egypt's legal framework to comply with MARPOL Annex VI SO_x emissions is 15-20%, and the International Maritime Organization (IMO) limits (Piccolo, 2023)
- Economic constraints: Lack of sufficient green investment incentives and the administrative fragmentation of environmental governance.

For example, Singapore's Port harnessed digital twin technology and reduced emissions by 30% (Karlsson et al., 2024) Yet Egyptian Ports don't use this technology in pollution control systems. Egypt's solar energy has not been used effectively till now, and other renewable energy sources remain largely untapped in the country(El-Naggar et al., 2025).

This research develops a proposal for Egypt by suggesting a combination of IMO decarbonization methods along with solutions for waste and biodiversity management into a single integrated model to cope with the latest trends in the environmental systems all over the world and achieve national goals as set in Egypt Vision 2030.

2- Literature Review

The implementation of modern technologies to optimize and mitigate the environmental impacts of maritime port operations is referred to as the modernization of EMSs. The modernization of EMS attracts global attention, with Port Rotterdam and Port Singapore being the frontrunners in port technological advancement. Moreover, artificial intelligence (AI) powered air quality monitoring systems and blockchain-based emission tracking systems have been deployed in these ports. These systems have greatly improved real-time data gathering, emission reporting, and meeting global environmental obligations. For instance, research conducted on Port Klang, Malaysia, reveals the importance of energy efficiency, waste handling, and sustainable equipment in the development of green port hubs(Jeevan et al., 2022). In the same vein, research on the application of renewable energy in seaports indicates the application of solar and wind energy technologies as a means of reducing carbon emissions(Elkafas & Seddiek, 2024).Despite these developments, the adoption of such technologies by Egyptian seaports remains relatively low. Their dependence on manual reporting systems makes it hard to measure emissions properly or employ predictive maintenance, such as Internet of Things (IoT) or AI devices, which are crucial for monitoring and decision-making processes.

2.1 Global Trends in Maritime Transport

2.1.1 Decarbonization and Green Technologies

Driven by the maritime decarbonization strategy put forth by the IMO in 2023, there has been a great shift towards decarbonization within the maritime industry. According to the strategy, there is a 40% reduction target set for carbon intensity by 2030(Chircop, 2019). Leading ports are actively switching from heavy fuel oil to adopt green ammonia and hydrogen fuels, thanks to scalable projects such as the Rotterdam Green Hydrogen Hub that establish infrastructure for bunkering zero-emission fuels. Additionally, shore power infrastructure is being deployed on a larger scale, as exemplified by the Port of Los Angeles's electrification efforts, which resulted in an astonishing 85% decrease in diesel particulate matter emissions (Mousavinezhad et al., 2024).

The circular economy is also expanding, such as the automation of ports like Hamburg, the integration of waste-to-energy plants that turn ship waste into energy, aligning with SDG 12 (Pisano, 2024). In the same manner, wind-assisted propulsion and carbon-capturing technologies are being introduced to transoceanic shipping, which has resulted in a 20-30% reduction in lifecycle emissions (Krantz et al., 2023).

2.1.2 Digitalization and Smart Port Technologies

Ports are being transformed with Digitalization, IoT-driven cargo tracking, and the use of AI for predictive maintenance. The Port of Singapore utilizes digital twins, which help improve traffic flow and reduce idle time by 25%, which has also led to reduced fuel consumption. Additionally, platforms like Trade Lens increase the visibility of the supply chain by transforming bills of lading and emissions reporting into digital forms, which allows for MARPOL Annex VI compliance (Philipp, 2020). Sophisticated vessels and AI-driven emissions monitoring have become some of the most important ways to achieve compliance in real-time (Sarantopoulos, 2024).

2.1.3 Green Infrastructure Innovations

Prominent ports are putting capital into solar-powered container cranes. The Port of Antwerp has adopted smart grids that mitigate the energy demand and supply imbalance, thus enjoying 35% energy autonomy (Notteboom et al., 2020).

2.1.4 Case Studies of Leading Ports

- Rotterdam (Netherlands): 27 % reduction in CO₂ from ports since 2016, achieved by AI satellite networks for air quality and LNG bunkering (Notteboom et al., 2020).
- Shanghai (China): Reduced port-associated emissions by 30% with hydrogen-powered terminal machinery and automated guided vehicles AGVs (Zhou et al., 2020).
- Los Angeles (USA): Developed a green corridor with Shanghai for tracking emissions with blockchain technology (Li et al., 2024).

2.1.5 Gap analysis

Enhancing the EMSs of Egyptian seaports needs to bridge fundamental gaps between existing practices and international best practices in sustainable maritime operations (Shahhat, 2019). This gap analysis is conducted across four dimensions, focusing on Egypt's problems in the recent academic and policy literature.

1. Technology Gaps in Digitalization and Decarbonization Efforts

The seaports in Egypt need to follow the leading ports such as Rotterdam and Singapore, which have integrated air quality monitoring systems and blockchain-driven emission tracking, as these ports still depend on manual reporting systems. While studies explore digital twins for port operations optimization, Egypt's ports still do not have IoT sensors for real-time data collection. Also, international developments in green hydrogen bunkering and shore power technology in Egyptian Port energy systems need to be developed (Klopott et al., 2023).

Gap: Resources available on smart port technologies (such as the digital twin project for the Port of Los Angeles) need to be developed in the Egyptian Ports, including insufficient grid coverage and the lack of investment for renewable energy integration (Salah et al., 2022).

2. Lack of Alignment with International Regulations Frameworks

The carbon emissions targets set by the international maritime industry are very ambitious, one being the reduction of carbon emissions by 40% by the year 2030 (Kotzampasakis, 2023). Egypt, however, has to develop its regulatory framework to cope with those goals. The national laws need to cope with international treaties regarding emissions control.

Gap: Most of the research concentrates on general policy frameworks that do not consider the intricacies of fragmented governance, where there is a considerable division of responsibilities among key institutions.

3. Financial and Institutional Barriers

Prominent ports were able to capitalize on public-private partnerships for funding sustainable initiatives, such as waste-to-energy plants, but Egyptian seaports face significant challenges in gaining access to green financing. Even though Egypt has a high potential for solar energy, the lack of incentives for private sector participation makes it difficult to deploy renewable energy technologies. While other countries have developed sizable funds for decarbonizing ventures, the Egyptian ports need to develop such instruments to promote large-scale environmental projects (Elswey, 2025).

Gap: Green financing needs to be developed in the Egyptian context. Also, the institutional barriers and lack of stakeholder coordination that are overarching the implementation of using renewable energy (Shaheen, 2023).

4. Custom Solutions for Enhancing Biodiversity and Developing Circular Economies at the Local Level

Such practices need to be developed in Egypt, where coastal systems are highly sensitive. Furthermore, while international frameworks provide action plans on how to conserve marine biodiversity. In addition, international focuses on circular economy practices tend to be on waste-to-energy systems (Lukkarinen et al., 2023) without considering such opportunities in Egypt as solar-powered desalination of ballast water.

Gaps: There are no solutions that seek to address the integration of solar energy into environmental management systems in Egyptian Ports (Tawfik et al., 2023).

3- Methodology

Using SWOT analysis in the evaluation of EMSs enables a holistic understanding of the performance and modernization of EMSs in Egyptian seaports. This framework makes it possible to assess what is being done well by Egyptian ports, what is not, what external opportunities could be taken advantage of, and what factors could impede forward movement (El-Bawab, M., & Dekinesh, 2021). What follows is a comprehensive discussion of how this framework is integrated with the existing EMSs in the Egyptian seaports

3.1.1 Strengths and Weaknesses

Strengths: One of Egypt's advantages is its position along the Suez Canal, one of the most important trade routes by sea in the world. This gives the Egyptian ports access to a huge volume of trade and economic activity around the globe (Mann, 2023). Container terminals and logistics centers already in place also make it easier to modernize the port infrastructure in Egypt (Elswey, 2025).

Weaknesses: Alongside these benefits, ports in Egypt also have a few internal issues. Emissions reporting is not done by new trends of smart systems, which makes the monitoring and management of environmental impacts ineffective. Existing laws, such as Law 4/1994, need to be developed to cope with international norms such as the new amendments of MARPOL Annex VI regulations. In addition, attempts to lower carbon emissions are stymied by the inadequate incorporation of renewable energy systems into port operations (Awad, 2023).

3.1.2 Opportunities and Threats

Opportunities: The development of green technologies across the world offers good chances to update the EMS systems implemented in Egyptian seaports (Elnabawi et al., 2023). For instance, the adoption of solar and wind energy would decrease the use of fossil fuels while maximizing solar energy use in Egypt (Elkelawy et al., 2025). There are also international regulations, such as the IMO Revised GHG Strategy (2023), which assist in achieving the sustainability objectives. There is also support for green investments in port facilities from international bodies like the World Bank, which provides financial aid.

Threats: External competitors encompass fines placed through systems like the European Union (EU) Emissions Trading System (ETS), which charges non-compliant vessels. Enhanced competition from ports like Rotterdam and Singapore also shows the need for modernization (Bugge & Stemsrud, 2024).

In Figure 1, the SWOT Quadrant for EMS in Egyptian Seaports, the diagram at hand explains the SWOT analysis in its quadrants as it pertains to the EMS operations in Egyptian seaports. The internal factors, which are denoted by strengths and weaknesses, depict the characteristics of the EMS, while the external factors of opportunities and threats depict the operating environment of the Egyptian Seaports.

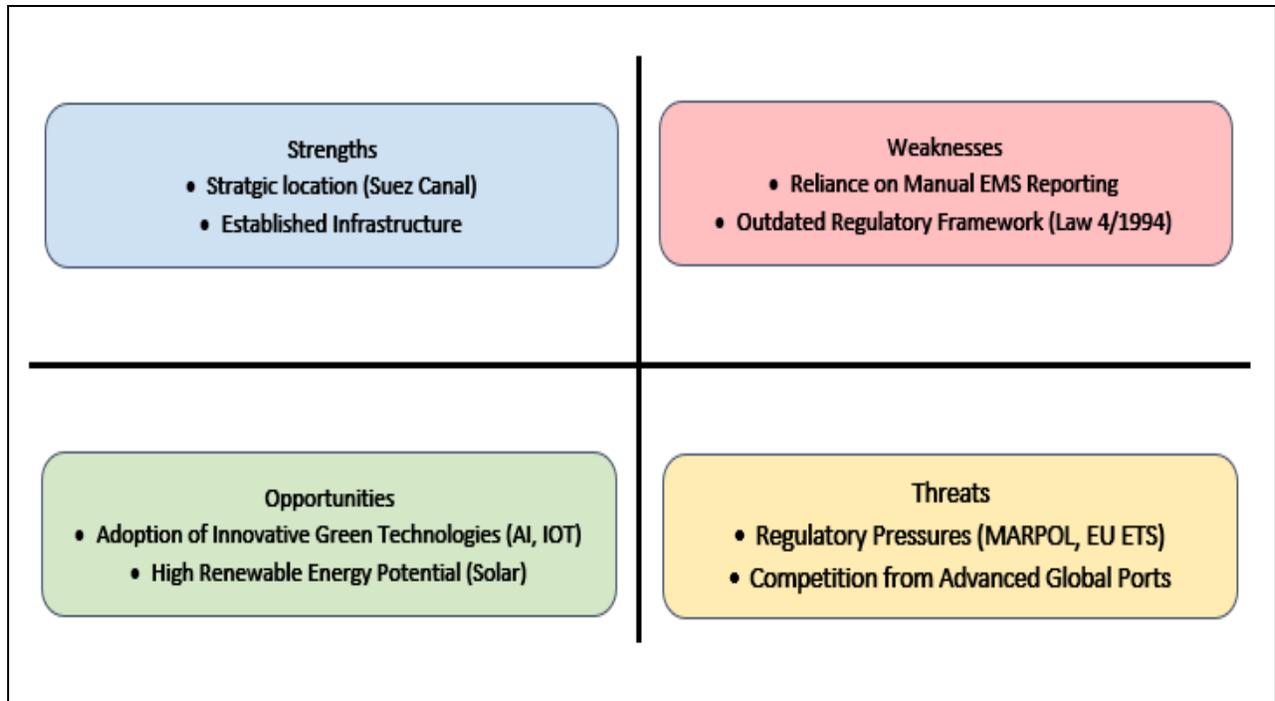


Figure (1): SWOT Quadrant Diagram for EMS in Egyptian Seaports

Figure (2) shows the Mind Map for SWOT Analysis for the EMSs in Egyptian Seaports. It outlines the current situation of the EMSs and establishes steps towards modernization by highlighting the SWOT Analysis.

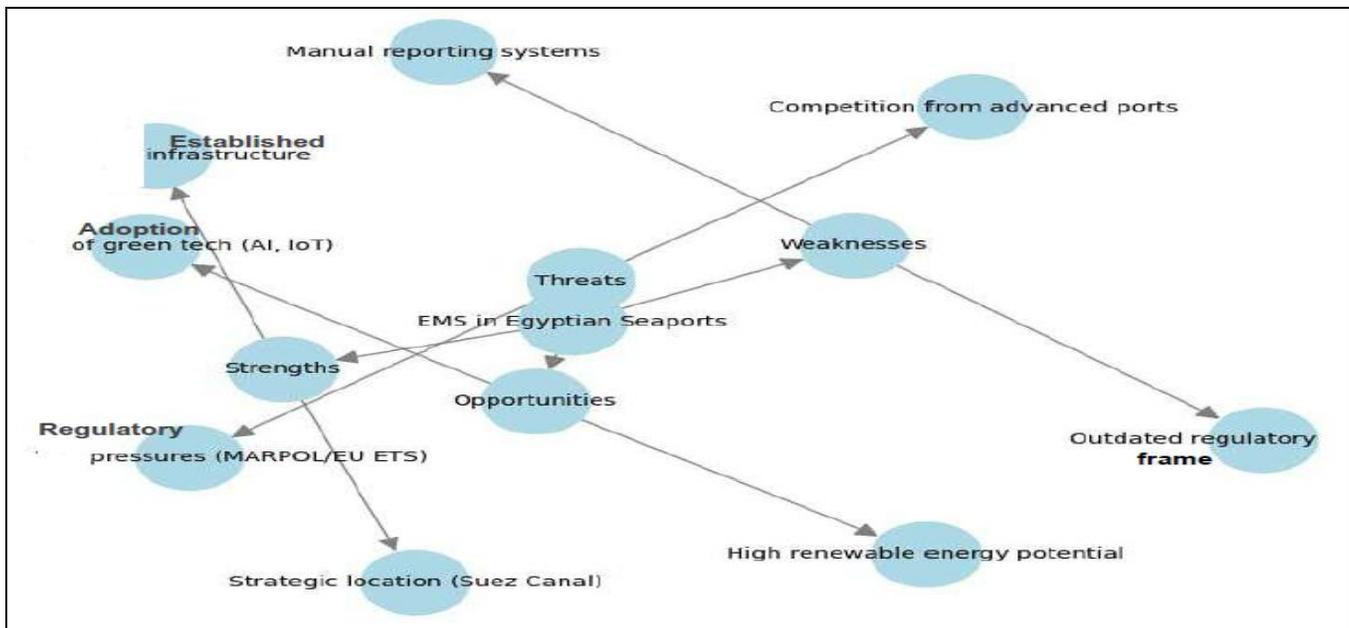


Figure (2): Mind Map for SWOT Analysis for EMS in Egyptian Seaports

3.2 Case Studies

Comparative Study of International Standards and Egyptian Ports Case Studies: Best Practices.

This comparative analysis studies the EMSs of Egyptian ports with three top world ports: Rotterdam (Netherlands) Port Klang (Malaysia), and Port of Los Angeles in the USA. The study examines four primary areas: Technological Integration, Regulatory Alignment, Financial Mechanisms, and Localized Solutions, helping to contribute to the update of Egypt's EMS, considering global shipping developments.

Table (1): Technological Integration

Port	Key Technologies	Egyptian Context
Rotterdam	Monitoring air pollution using AI technology, tracking carbon emissions through blockchain technology, and green hydrogen bunkering(Mba, 2024).	Dependence on manual reporting sources; does not include AI or blockchain technology.
Port Klang	Waste management systems enabled by IoT technology, and equipment efficiency rating to energy use(Bahri et al., 2025).	Adoption of IoT technologies remains low and waste is still tracked manually.
Los Angeles	Shore power systems, digital twins for traffic optimization(Klar et al., 2023).	No application of a digital twin; Energy systems reliant on fossil fuels.

Table (1) shows the key insights of the gap: Egyptian ports need to develop advanced technologies such as AI, blockchain, and IoT for emissions monitoring and reduction in real time

Recommendation: Focus attention on implementing pilot projects for AI-based air quality management systems and shore power systems.

Table (2): Regulatory Alignment

Port	Regulatory Framework	Egyptian Context
Rotterdam	Adheres to IMO's Revised GHG Strategy and MARPOL Annex VI compliance(Chairunnisa, 2024).	Law 4/1994 needs to be developed; SOx and NOx emissions surpass the IMO limits by 15-20%.
Port Klang	The national green port policy incorporates SDG 14 with the conservation of habitats (Rika Widianita, 2023).	Legal frames need to be developed to protect marine biological diversity.
Los Angeles	Observing the standards put in place by the California Air Resources Board and compliance with the EU ETS regulations.	There is no effective enforcement system for emission penalties.

Table (2) shows the key insights of the gap: the Egyptian ports need to develop port-specific mechanisms of green financing, such as grant-funded green bonds and foreign aid

Recommendation: Develop the green port fund mechanisms in the country and partner with international institutions like the World Bank for blended financing.

Table (3): Financial Mechanisms

Port	Funding Strategies	Egyptian Context
Rotterdam	Public-private partnerships; European Union Green Bonds for Hydrogen Infrastructure (Jacopo Maria Pepe, 2023)	A fixed number of green financing opportunities are available within a limited timeframe, project implementation delays caused by the administrative processes in approvals.
Port Klang	Government finance for projects to develop renewable energy sources(Bahri et al., 2025)	Motivation is needed to solicit investment in the private sector
Los Angeles	Green shipping corridor funds, California climate investments grants (Densberger & Bachkar, 2022).	Limited decarbonization financial resources

Table (3) shows the key insights of the gap: Egyptian ports need to develop more financing tools like green bonds or international grants.

Recommendation: Set up a national Green Port Fund and create partnerships with international organizations such as the World Bank for blended finance approaches.

Table (4): Localized Solutions

Port	Sustainability Initiatives	Egyptian Context
Rotterdam	Waste-to-energy plants(de Leeuw & Koelemeijer, 2022).	Not implementing circular economy strategies; pollution management is mostly reactive, material pollution
Port Klang	Conservation of mangroves; illumination of the port by solar-powered lanterns(Hattam et al., 2021).	More safeguarding of habitats; coral reefs in the Red Sea are susceptible to deep-sea dredging.
Los Angeles	Solar-powered cranes; zero-emission terminal equipment(Port of Los Angeles, 2023).	Untapped solar potential annually.

Table (4) shows the key insights of the gap: The potential for solar energy in Egypt remains largely untapped, and EMS strategies need to be developed to harness biodiversity.

Recommendation: Develop systems for using water desalinated through solar energy for ballast water recycling, and use bio-receptive materials for coastal region construction and development.

Table (5): Synthesis and Recommendations

Dimension	Benchmark Ports	Egypt’s Action Plan
Technology	AI, blockchain, and shore power.	Pilot AI monitoring in the port's shore power supply.
Regulatory	Policies aligned with the IMO/SDGs.	Reform the legal framework to be developed to implement MARPOL Annex VI provisions.
Financial	Green Bonds in Public-Private Partnerships PPPs.	Establish a national green port fund to attract climate grants from the United Nations Development UNDP Programme.
Localized Solutions	Circular economy. Conservation of biomes.	Cranes Powered by Solar Energy; Protection Areas for Coral Reefs

Table (5) links the actions needed to modernize EMSs in the Egyptian seaports with the global best practices that can be adopted. It is built around four key areas: Technology, Regulatory, Financial, and Localized Solutions, and articulates thorough action plans based on leading ports for the specific needs of Egypt as shown:

- Technology: The suggestion to start with AI-based air quality monitoring systems at ports, along with the gradual provision of shore power systems, shows a willingness to embrace advanced technologies. This is compatible with the present digitalization and decarbonization trends in benchmark ports such as Rotterdam and Los Angeles.
- Regulatory: Changing Egypt’s archaic laws, like Law 4/1994, and applying MARPOL Annex VI has compliance issues that fill basic gaps in regulatory alignment. This guarantees that Egyptian seaports have international port environmental systems compliance and reduces the risks of non-compliance penalties.
- Financial: Setting up a national green port fund as well as taking advantage of global financing like green bonds and UNDP climate grants shows initiative to mitigate financial barriers. This is critical for the funding of large-scale EMS modernization scheme projects.
- Localized Solutions: The emphasis on solar-powered cranes and the management of protective zones for coral reefs illustrates the importance of specific integrated environmental assets in Egypt's EMS. These localized solutions advance global sustainability while accommodating regional ecology. The table summarizes the major steps in a clear manner for developing the EMS of Egyptian seaports to make them competitive internationally and ensure ecological preservation.

4- Results

The result of this study exposes an important need for the Egyptian EMSs to be developed at their seaports regarding technological effort, compliance, financing, and contextualization. It highlights

another gap between the national practices of Egypt and sustainable targets in global maritime practices, providing evidence of potential modernization challenges and aids.

4.1 Technological Gaps

Compared to other pioneer world ports, ports in Egypt need to be developed in this aspect of technology. While Rotterdam and Los Angeles ports use AI systems for real-time air quality management and emissions control through blockchain, ports in Egypt depend on systems that use manual reporting. An example is Rotterdam, where AI systems adoption for air quality management has increased CO₂ emission reduction (Elnabawi et al., 2023). The absence of IoT sensors for waste management and shore power infrastructure increases the ineffectiveness. This technological gap curbs full compliance with MARPOL Annex VI requirements regarding emissions of sulfur oxide (SO_x) and nitrogen oxide (NO_x) alongside Egypt's ability to take part in a green shipping corridor.

4.2 Regulatory Gaps

Egypt's regulatory framework for EMSs still needs to be developed to cope with international standards. The pillar of national environmental legislation, Law 4/1994, needs to be amended to comply with the IMO GHG Strategy to decrease SO_x emissions of Egyptian ports.

Financial Gaps

Egyptian ports do not have access to the same financing instruments that both Rotterdam and Los Angeles do, which are public-private partnerships (PPPs) along with green bonds used to fund projects such as hydrogen bunkering infrastructure. Even though Egypt has potential for solar energy (Abdoos et al., 2025), financed renewable energy projects are not being used to their best use. Along with the lack of a national green port fund, further stagnates any progress. For example, Singapore has a model of decarbonization as Singapore's Maritime Green Future Fund

Localized Solutions

The particular context of Egypt necessitates the modification of the existing EMS framework. Circular economy practices need to be developed in Egypt, for example, solar-powered desalination of ballast water for use in waste-to-energy plants, and using solar-powered cranes and lighting systems in the Egyptian ports.

5- Discussion

The upgrading of EMSs in Egyptian seaports requires an integrated strategy that involves new technologies, appropriate legislation, adequate funding, and the engagement of local stakeholders. This section integrates the study's results within the global context of maritime sustainability and sets forth practical alternatives to address the discrepancy between Egypt's practices and the established international standards.

5.1 Technological Modernization and Digitalization

The Egyptian seaports significantly differ from Rotterdam and Singapore Ports in adopting advanced features such as artificial intelligence (AI) monitored air quality, emissions tracking through IoT, and supply chain blockchain technology. For example, Rotterdam's AI achieved a

27% reduction in CO₂ emissions (Durlík et al., 2024). Singapore ports digitalized traffic flow which decreased idle time by 25% (Yu et al., 2023).

Egypt's Ports' EMSs need to be developed to cope with the new amendments of MARPOL Annex VI and the IMO GHG Strategy. The phased implementation of shore power infrastructure, demonstrated by the Port of Los Angeles, has the potential to eliminate auxiliary engine emissions from berthed vessels, therefore complying with the 2030 decarbonization target set by the IMO (Mousavinezhad et al., 2024). Workforce skilling for digital tools, then pilot projects in AI adoption for the Egyptian ports, could act as a primary step to greater technological integration for the Egyptian Ports development according to Egypt Strategy 2030.

5.2 Regulatory Reforms and Governance

The foundation of Egypt's environmental policy, Law 4/1994, needs to set mandatory limits for the reduction of carbon emissions and has no provisions for controlling emission discharges. Such gaps undermine compliance with MARPOL Annex VI and the IMO Revised GHG Strategy (2023). Also, it should be adapted to the EU Emission Trading System (ETS). In contrast, Rotterdam was able to achieve a remarkable reduction in SO_x emissions, which was compliant with MARPOL Annex VI, due to its regulation (Papadopoulos et al., 2022).

5.3 Financial Mechanisms and Green Financing

The lack of mechanisms for green financing, including green bonds and public-private partnerships, limits Egypt's funding for renewable energy projects despite its ability to produce solar energy all year. Establishing a national green port fund would provide funding for solar energy and shore power systems. In addition, boosting investment by the private sector through tax incentives or expedited permit processes would further facilitate the shift to renewable energy.

5.4 Localized Solutions for Biodiversity and Circular Economies

Port management systems all over the world have incorporated bio receptive concrete to improve marine biodiversity to be compatible with SDG 12. Ports in Egypt need to develop plans in place to alleviate the negative consequences of dredging on the coral reefs. Also, constructing solar-powered desalination systems for ballast water reuse and setting up ecosystem service conservation zones could simultaneously solve these problems and take advantage of Egypt's solar energy. These policies would decrease the dependency on fossil fuels as well as transform Egyptian ports into leaders of sustainable maritime practices in the region.

5.5 Limitations and Future Research

Evaluating the socio-economic impacts of the modernization of EMSs, such as the employment impacts of green technology and the economic evaluation of renewable energy investment one of the best practices in future research related to modernizing environmental management systems in Egyptian seaports to align with global maritime transport trends. In addition, examining AI-powered digital twins for Egyptian ports may yield more detailed information regarding the reduction of emissions and efficiency of operations.

5.6 Policy and Operational Implications

The EMS modernization strategies are underpinned by Egypt's Vision 2030 and the National Strategy for Green Ports 2030. Decision makers need to implement a mixed approach based on the regional IMO decarbonization goals. Addressing the disparity between the global practices and Egypt's EMS features appears to necessitate a multifaceted approach that incorporates technological advancement, institutional strictness, financial creativity, and ecosystem protection. While Egyptian seaports are strategically located, their adoption of a proactive environmental leadership style would enable them to shift from habitually combating pollution as a reactive mechanism to controlling it. Not only will this drastic change result in better alignment with international standards, but it will also cement Egypt's position as a competitive maritime hub in the world.

6- Conclusion

The developing trends in maritime transport offers Egyptian seaports the golden gate to modernize their EMSs and put it in for global standards. There are certain hurdles to overcome, such as: lack of appropriate technology, regulatory mismatches, strained finances, and local resource idleness. These hurdles pose a unique challenge, but they also provide opportunities for growth and advancement. The abundant solar energy resources available to Egyptian ports, combined with their strategic geographical position, provide a fallback for adopting advanced technologies such as AI powered emission surveillance, blockchain cargo tracking, and shore power systems. Egyptian seaports poised to rapidly embrace sustainable practices by adopting international regulatory standards like the ammendments in MARPOL Annex VI and mobilizing green financing. This is achievable through realignment of local regulations to international ones and paving the gaps with green financing. Also, local setting the invariant guard rails focused on enhancing environmental performance goes further to extend Egypt's pivotal position in Arabian maritime sustainable roduction leadership.

Recommendations

To bridge the gap between Egyptian port EMSs and global maritime sustainability benchmarks, this study provides specific recommendations under four categories, namely policy alignment, technological modernization, financial innovation, and localized solutions. The study has borrowed these strategies from the vast array of best practices in leading ports such as Rotterdam, Singapore, and Los Angeles while considering Egypt's unique infrastructure set-up, regulation system, and ecology.

6.1 Policy Alignment

6.1.1 Regulatory Overhaul:

- Make Law 4/1994 consistent with international conventions such as MARPOL Annex VI and IMO Revised GHG Strategy (2023). Set binding targets for carbon intensity reduction (40% by 2030; 70% by 2050), penalizing non-compliance similar to the EU Emissions Trading System (ETS).

- Centralized Environmental Governance: Establish a unified regulatory authority to streamline enforcement and eliminate fragmented oversight.

6.1.2 Incentive Frameworks:

- Give tax holidays and subsidies on renewable energy investments done through the private sector. Rotterdam's experience in seeking public-private partnerships to fund its green hydrogen bunkering can be replicated.
- Establish a Green Port Certification Program that rewards adherence to IMO standards by giving discounts on port fees or fast-tracking berthing priority for vessels using low-carbon fuels.

6.2 Technological Modernization

6.2.1 EMS digitization:

- Carry out a pilot of AI-driven monitoring systems for air quality and emissions in Egyptian ports, using the same artificial intelligence that was employed in Rotterdam to achieve 27% less carbon dioxide emissions.
- Adopt logistics platforms with blockchain capabilities to improve transparency in emission reporting and waste management, which matches Singapore's digital twin frameworks.

6.2.2 Shore power infrastructure:

Start introducing shore power systems into high-traffic berths in the Egyptian ports to eliminate reliance on auxiliary engines. Los Angeles realized an 85% reduction in diesel particulate matter by electrification; Egypt could reproduce this either through UNDP or World Bank financing.

6.3 Financial Innovation

6.3.1 National Green Port Fund Establishment:

- Attract external grants (such as UNDP Climate Programs, and EU Green Programs).
- Create green bonds focused on port infrastructure leveraging Egypt's strategic location along the Suez Canal to get global investors.

6.3.2 Public-Private Partnerships (PPPs):

- Collaborate with renewable energy developers installing solar farms near ports, taking advantage of Egypt's solar potential. A good example is Port Klang.

6.4 Localized Solutions

6.4.1 Biodiversity Conservation:

- Classify the areas around Red Sea ports as coral reef protection zones, and impose restrictions on dredging that will help to reduce the degradation of ecosystems. Antwerp has used bioreceptive concrete to boost marine biodiversity, which can be copied.
- Incorporate circular economies through the conversion of waste generated by ships into energy. Rotterdam's waste-to-energy facilities produce 15% of the port's electricity; Egypt could do it with solar-powered desalination for ballast water reuse.

6.4.2 Solar-Driven Infrastructure:

- Construct terminals to install solar-powered cranes and automated guided vehicles (AGVs), based on the model developed by Shanghai that reduced terminal emissions.

6.5 Implementation Roadmap

Dimension	Global Benchmark	Egypt's Action Plan	Timeline
Technology	AI emissions monitoring by Rotterdam Port	Pilots' AI systems in Egyptian ports	2025–2026
Policy	EU ETS Compliance Frameworks	Implement changes to Law 4/1994 in accordance with the International Maritime Organization Goals.	2026–2027
Financial	Singapore's Maritime Green Future Fund	Initiate the National Green Ports Fund	2025–2026
Localized Solutions	Antwerp's bioreceptive concrete.	Establish protruded boundary regions for coral reef conservation in the Red Sea.	2025–2027

7- Future Research Directions

To facilitate the realignment of Egyptian seaports with global maritime sustainability trends, the following research approaches are necessary for accelerating the development of Environmental Management Systems (EMS) intended for Marine Ports:

- Port Operations Technological Advancement: Analyze the implementation of AI-powered digital twins and blockchain technology to streamline port activities and improve the accuracy of emissions reports. Investigate the potential of Egypt's infrastructural limitations, like grid capacity and renewable energy integration (solar-powered systems), to expand the scope of these innovations.
- Legal Framework Social and Economic Impact Studies: Estimate the socio-economic advantages and disadvantages of a compliance-aligned revision of Egypt's Law 4/1994 that includes mandatory carbon reduction goals of 40% by 2030 and 70% by 2050, and slaps EU ETS-like fines.
- Finance Models for Development Aid: Construct models for sovereign green bonds, PPP projects, and international climate change grants to finance shore power facilities and hydrogen bunkering infrastructure. Also explore Rotterdam's initiatives as a case study to adapt Egypt's investment in green hydrogen.
- Domestic Renewable Initiatives: Create solar-powered ballast water desalination systems and test bio receptive concrete to lessen the dredging's impact on corals of the Red Sea and further the efforts of SDG 14.
- Stakeholder Collaboration: Examine interdisciplinary approaches to engage multiple stakeholders, such as shipping firms and local communities, to collaboratively develop strategies for EMS modernization. Egypt can learn from the EU green corridors, such as Rotterdam to Shanghai.

- Longitudinal Monitoring: Monitor emission decreases, as well as employment opportunities arising from green technology and renewable undertakings' expenses in relation to returns within the framework of Egypt Vision 2030, and the National Strategy for Green Ports 2030 to prove compliance.

These proposed research topics focus on the deficiencies in technology, policy, finance, and ecology, and ensure that Egyptian seaports transform into sustainable, competitive international and regional centers. Emphasis on tailored collaborative innovation should further advance Egypt's integrated maritime and environmental developmental goals.

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Cybersecurity Threats in Maritime Autonomous Surface Ships Navigating Canals and Narrow Channels: A Risk Assessment Using STPA-Safety/Security and Fuzzy-AHP

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المستخلص

تُعد القنوات البحرية والممرات الضيقة عناصر حيوية للتجارة العالمية، إلا أن طبيعتها المحدودة تنطوي على مخاطر كبيرة، خاصة مع الاعتماد المتزايد على التقنيات الرقمية في ملاحاة السفن. تستكشف هذه الدراسة التهديدات الأمنية السيبرانية التي تواجه السفن السطحية البحرية ذاتية القيادة (MASS) العاملة في هذه البيئات، مع التركيز على الهجمات السيبرانية المحتملة التي قد تؤدي إلى حوادث مثل الجنوح، والاصطدام، وفقدان السيطرة على الدفع. باستخدام منهجية تحليل النظم النظرية للأمن والسلامة والأمن (STPA-Safety/Security) المدمجة مع الأسلوب الهرمي الضبابي (F-AHP)، تحدد الدراسة وتُصنف التهديدات الرئيسية، بما في ذلك تشويش نظام تحديد الموقع المعتمد/نظام التعريف الآلي (GPS/AIS)، تشويش الاتصالات، والسيطرة الخارجية على وسائل الدفع والتوجيه. تم التحقق من سيناريوهات التهديد من خلال مدخلات الخبراء باستخدام طريقة دلفي، مما يوفر تقييماً شاملاً للمخاطر. تسلط النتائج الضوء على الحاجة الملحة لتعزيز إجراءات الأمن السيبراني، مثل أنظمة الملاحاة الاحتياطية، وقنوات الاتصال الآمنة، وتحسين تدريب المشغلين. تساهم الدراسة في الأدبيات المتعلقة بالأمن السيبراني البحري من خلال تقديم منهجية منظمة لتقييم وتخفيف المخاطر السيبرانية في عمليات السفن ذاتية، لا سيما في الممرات المائية الضيقة.

Abstract

Maritime canals and narrow channels are critical for global trade, yet their confined nature poses significant risks, especially with the increasing reliance on digital technologies in ship navigation. This study investigates cybersecurity threats to Maritime Autonomous Surface Ships (MASS) operating in these environments, focusing on potential cyber-attacks that could lead to accidents such as grounding, collisions, and loss of propulsion control. Utilizing the System-Theoretic Process Analysis for Safety and Security (STPA-Safety/Security) combined with Fuzzy Analytic Hierarchy Process (F-AHP), the study identifies and prioritizes key threats, including GPS/AIS spoofing, communication jamming, and thruster override. Expert input via the Delphi method validates the threat scenarios, providing a comprehensive risk assessment. The findings highlight the urgent need for enhanced cybersecurity measures, such as redundant navigation systems, secure communication channels, and improved operator training. The study contributes to

maritime cybersecurity literature by offering a structured methodology for assessing and mitigating cyber risks in autonomous ship operations, particularly in confined waterways.

Keywords: Maritime Autonomous Surface Ships (MASS) - Cybersecurity - STPA Safety/Security - Risk Assessment - Delphi Method - Autonomous Ship Operations

1- Introduction and Literature Review

Maritime canals and narrow channels play a critical role in international sea trade and cargo movements. The Suez Canal and Panama Canal for example are marvelous pieces of engineering linking oceans and seas making the maritime trade possible for a cost-efficient transfer of goods between continents (Akhter, 2018; Zhang et al., 2023). However, the narrowness of these channels poses a set of challenging factors, such as shallow depths, narrow curves, and presence of locks (Chorev, 2023; Thomas, 2022). The smallest disruptions in these channels, due to accidents, environmental factors, or due to cyber-attacks, can lead to a large amount of economic loss along with environmental destruction. For example, Suez Canal incident of grounding of the Ever Given in 2021 led to a six-days closure, disrupting supply chains all over the world and incurring an estimated daily loss of trade of \$9.6 billion (Aydogdu, 2022).

Safe navigation of ships along such confined channels is a vital matter for canal authorities, sea operators, and policy makers alike (Kong et al., 2024). The increase in sophistication of ship systems coupled with enhanced reliance on digital technologies is opening new avenues of vulnerability which must be countered in a bid for maritime operation to be secure and secure (Akpan et al., 2022).

Increased digital technologies in marine activities have opened new lines of vulnerability in seaborne vessels and seaports (Melnyk et al., 2023). Navigation, communications, and critical safety systems in seaborne ships have also become a target for cyberattack, which is a high-risk threat in seaborne activities. Vulnerability in some functions in a seaborne ship, i.e., Automated Identification System (AIS), Electronic Chart Display Information System (ECDIS), in addition to satellite communications, have also been reported (Bothur et al., 2017). The Global Positioning System (GPS) is at high risk, which demands multiple systems be utilized to obtain the ship's position and provide an aid to navigation (Androjna et al., 2020). The remedy demands a full around-the-clock remedy, which consists of risk estimation, implementing cybersecurity measures, as well as following industry-led measures (Kapalidis et al., 2022). Solutions proposed involve implementing a concept of a "Defence-in-depth," increased manufacturers' cybersecurity measures, technical as well as procedure-based countermeasures (Androjna et al., 2020; Bothur et al., 2017). There is also high revolution in seas because of MASS and remote ship technologies (Issa et al., 2022). These technologies have a high possibility with enhanced operation, minimization of human error, as well as cost-effectiveness. The autonomous ships can operate at best in canals as well as narrow water bodies, wherein precision is necessary with a quick decision (Zhang et al., 2024). The new technologies brought these vessels as a new threat in terms of security in the cyber-world (Tabish & Chaur-Luh, 2024). The sector is highly dependent on digital

technologies, network communications, hence is highly susceptible towards cyberattack. Threats from these attacks can be in terms of GPS spoofing, jamming communications, as well as ransomware attacks (Androjna et al., 2020). Automation in the marine is in full swing, making it more crucial than ever before that these risks are addressed. The threat of autonomous ship cyberattack can have catastrophic outcomes, which involve grounding, collision, loss of steering in canals in addition to the narrow water structure with complex and confined geometry (Ben Farah et al., 2022). The risks have the power to cause disruption in navigation, communications and drive functions, which lead to accidents as well as interruptions in operation. For example, a ransomware attack on shipping company Maersk in 2017 caused mass disruptions in its operations all over the globe, showcasing the susceptibility of the sea industry to cyberattacks (Senarak, 2024).

This study aims to evaluate cybersecurity risks impacting autonomous and remotely operated ships navigating narrow waterways, focusing on vulnerabilities in vessel command, propulsion, navigation systems, and waterway infrastructure. It seeks to identify cyberattack-induced threats, conduct component-level analyses, and assess risks associated with communication networks linking ships to control centers, onboard sensor data transmission, and navigational command signals. The research emphasizes mitigating vulnerabilities to ensure safe transit in constrained environments by proposing strategies to strengthen system resilience and prevent disruptions to operational integrity.

2- Methodology

To achieve the objective of the study the following is approach. System-Theoretic Process Analysis for Safety and Security is a highly mature process for identifying potential threats and is widely practiced in risk-heavy industries (Basnet et al., 2023). The process is an integrated process in which safety and security factors have been amalgamated in a combined process. The process is an extension of classical STPA (System-Theoretic Process Analysis), for threat and risk assessment. STPA- Safety/Security directly addresses interdependency between security and safety in complex systems, realizing these two factors have a greater interdependency, especially in modern systems such as driverless cars, industrial automation systems, and critical infrastructure. In sea navigation, STPA is particularly appropriate in analyzing threats of cybersecurity which may have an impact on operation of a vessel (de Souza et al., 2020). STPA in electric power and smart-control systems has shown the contribution of safety-critical threats (Li et al., 2024). Furthermore, STPA-Safety/Security is recognized as an effective tool for analyzing security and safety concerns in complicated systems (Gad, 2023). More recently, its applicability is being taken to cyber-physical systems (Span et al., 2018).

Glossary of Key Methodological Terms

STPA-Safety/Security Framework

The System-Theoretic Process Analysis for Safety and Security (STPA-Safety/Security) is an extension of traditional STPA that simultaneously analyzes safety and security risks in complex cyber-physical systems. This integrated approach recognizes that modern maritime systems require

joint consideration of both accidental failures (safety) and malicious threats (security). The framework identifies Unsafe Control Actions (UCAs) that could lead to system hazards, whether caused by technical faults or cyber intrusions (Leveson, 2011; de Souza et al., 2020).

Core Analytical Components

Unsafe Control Actions (UCAs): Scenarios where control commands either fail to execute, execute incorrectly, or execute at inappropriate times due to either safety-related system failures or security-related compromises.

Safety Constraints: System design requirements that prevent physical failures (e.g., "propulsion systems must maintain minimum redundancy levels").

Security Constraints: Cyber-specific protections against malicious acts (e.g., "all navigation data inputs must be cryptographically authenticated").

2.1. STPA-Safety/Security Framework

The current study utilises STPA- Safety/Security in investigating potential interactions between cyber threats and sea technology when a ship is navigating in canals and narrow channels. The existing literature has utilised STPA- Safety/Security in investigating threats in unmanned vehicles (Li et al., 2024), threats of sea business piracy (Yuzui & Kaneko, 2025). The objective of STPA-Safety/Security is identifying threats which can occur when a navigation system of a vessel is being hacked in narrow channels of water. In an effort of strengthening the analytical process, a review of the ship accidents occurred in the narrow channels and in confined waters is done.

The proposed study process is based on these rudimentary steps:

1. Identification of Possible Accidents and Hazards
2. Developing a Threat Analysis at the Component Level
3. Identification of Unsafe Control Actions
4. Threat Scenario Analysis

While STPA-Safety/Security is valuable in threat scenario identification, it is difficult to precisely estimate each scenario probability.

To conduct the STPA-Safety/Security, a study on ship accidents in canals is necessary. A study on 98 accidents in (2020 – 2024), out of which 78 occurred at port, channel, and coastal water areas, from IMO GISIS database. The majority of serious accidents involved groundings at channel fairways as well as in lock areas, which are likely to involve serious operational disruption in these accidents

2.2. Fuzzy Analytic Hierarchy Process (F-AHP)

The study employs F-AHP to address the inherent uncertainty and subjectivity in assessing cybersecurity risks for MASS. This approach was specifically selected due to three compelling advantages over conventional methods: (1) its capacity to mathematically represent linguistic variables and expert preferences through triangular fuzzy numbers (Mamdani, 1977; Natarajan et al., 2022; Tesfamariam & Sadiq, 2006), (2) its effectiveness in scenarios with limited quantitative data, and (3) its compatibility with maritime cybersecurity assessments (Khan et al., 2024).

The F-AHP methodology was implemented through a rigorous four-phase process: (1) hierarchical modeling of decision criteria, (2) collection of pairwise comparison judgments using linguistic scales, (3) conversion to fuzzy numbers and weight calculation, and (4) defuzzification to derive crisp priority weights (Kubler et al., 2016). Judgment consistency was validated through the consistency ratio ($CR < 0.1$) as per Saaty (1990) standards. This structured approach enabled the effective integration of Delphi-derived expert knowledge with quantitative analysis, particularly valuable in data-scarce canal navigation scenarios.

Expert validation constituted a critical component of the methodology, with practitioner selection based on stringent criteria including professional qualifications in ship operations, risk assessment, and cybersecurity (Bolbot et al., 2020). The researchers comprised specialists with demonstrated experience in maritime accident investigation and cybersecurity assessment. Structured expert discussions, including live exchanges, were conducted to mitigate the limitations of traditional cyber threat analyses that often over-rely on IT specialists without adequate maritime operational context (Biswas et al., 2022). This multidisciplinary approach ensured both the validity of the STPA framework and the practical relevance of the F-AHP outcomes, effectively bridging the gap between theoretical risk assessment and operational maritime requirements.

$$\text{equation (1)} \quad w_i = \frac{1}{n} \sum_{j=1}^n \frac{a_{ij}}{\sum_{k=1}^n a_{kj}}$$

$$\text{equation (2)} \quad \text{Consistency Index} = \frac{\lambda_{max} - n}{n - 1}$$

$$\text{equation (3)} \quad M_{crisp} = a + \frac{(c-b)}{4}$$

Explanation of F-AHP Equations and Analytical Process

The study employed three critical equations to operationalize the Fuzzy AHP (F-AHP) methodology for maritime cybersecurity threat assessment. Equation (1) calculated normalized criterion weights (w_i) by aggregating and normalizing pairwise comparison matrices from expert judgments, transforming linguistic assessments of threat severity into quantifiable priorities. Equation (2) derived the consistency index (CI) to validate expert judgment reliability by comparing the principal eigenvalue (λ_{max}) against matrix dimensions, ensuring all evaluations met Saaty's threshold ($CI < 0.1$). Equation (3) converted triangular fuzzy numbers (a, b, c) into crisp values (M_{crisp}) through centroidal defuzzification, preserving uncertainty ranges while enabling precise threat ranking. Together, these equations systematically quantified expert-derived threat assessments while maintaining mathematical rigor, directly supporting the prioritization of risks. The resulting weights were further validated through Delphi rounds, ensuring alignment between computational outputs and practitioner expertise.

2.3. Delphi Method for Expert Validation

Due to a lack of empirical data on cybersecurity risks in canals and narrow channels, the process is crucial in capturing opinion as well as consensus on complex issues. In ship cybersecurity, the Delphi process can be utilized in closing gaps in standardized threat models and in risk assessment

methods, specifically in autonomous ships (Erbaş et al., 2024). The Delphi process is a great tool in risk assessment in analyzing risks in a variety of fields, specifically in ship cybersecurity (Lamii et al., 2022). The Delphi process is crucial in detecting manufacturing industries' cyber-physical systems, Internet of Things (IoT) network, cybersecurity risks (Chowdhury et al., 2022; Singh et al., 2023). The practitioners, though, held more in terms of disagreement as opposed to in terms of consensus in a study on Systems of Systems (SoS) vulnerability, which calls for more studies on a consensus on complex system vulnerability (Olivero et al., 2022). Results from these studies direct towards the need for systematic approaches such as Delphi in tackling seaborne cybersecurity issues.

The structured and live discussions are done through Zoom online meetings with 5 experts in different disciplines as mentioned in Table 1. Two online meetings are done for around 55 minutes each to verify the STPA-Safety/Security and to reach the consensus agreement on the logical scenario.

The Delphi method was rigorously applied through three iterative rounds to establish expert consensus on maritime cyber threats. In the initial round, five domain specialists (Table 1) independently evaluated STPA-derived threat scenarios using structured questionnaires. The second round employed statistical aggregation of responses (mean \pm 1 SD) and anonymized feedback to reconcile divergent assessments. Final consensus was achieved in Round 3, with Kendall's coefficient of concordance ($W = 0.78, p < 0.01$) confirming strong inter-rater reliability. This process specifically addressed the subjectivity of threat likelihood estimation. Experts provided weighted adjustments to account for canal-specific factors, which were subsequently incorporated into the F-AHP calculations through defuzzification of triangular fuzzy numbers (Equation 3).

To assess the likelihood of each threat scenario, the Delphi method was employed, involving two rounds of expert evaluations. The Delphi panel, consisting of five experts with diverse backgrounds, validated the threat scenarios and their associated risks. The Fuzzy-AHP methodology was then applied to calculate the weight of each security threat, as shown in Table 2. This table demonstrates the impact of key factors, such as monitoring of target locations, reaction time during operations, and the proximity of the target across various scenarios.

Table 1 Experts' Qualifications

Expert	Academic Qualification	Specialization	Years of Experience	Professional Qualification
Expert 1	Master CoC	Master F. G	15+	Master Mariner
Expert 2	Chief Engineer CoC	Chief Engineer	10+	Marine Engineer
Expert 3	MSc	Class Surveyor	20+	Ship Engineer
Expert 4	PhD	IT Engineer	15+	Ethical Hacker / IT Engineer

Expert 5	Master CoC	Pilotage operation	20+	Marine pilot
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3- Data Analysis and Discussion

Step 1: Define accidents and risks

The methodology STPA-Safety/Security was adopted in order to identify and analyze critical accidents that can occur in transits in canals as a result of cyber-attack. STPA-Safety/Security is ideally placed in analyzing complex systems such as autonomous vessels because it incorporates both safety and security, which allows analyzing likely hazards from a global perspective. The research focused on ship control systems' interaction with each other, with the surroundings in canals, as well as with threat from cyberattacks. The following findings were identified through the accident's investigation reports extracted from the IMO GISIS. Three critical incidents that can be identified from step 1 are grounding, collision with lock or bank, and propulsion control loss. All these three incidents have definite unsafe control activities (UCAs), which can be a result of a cyber-attack. In the following. The authors describe in which way these accidents have been identified as well as corresponding UCAs.

1. Grounding

Grounding is a significant risk during canal transit since the waterways are narrow and typically shallow. STPA- Safety/Security analysis identified that grounding could occur if the navigation systems of a ship are breached, which leads to erroneous positioning or route information. GPS/AIS'S spoofing is the primary UCA that is associated with grounding. In this case, a hacker manipulates the GPS or AIS information of a ship, and the ship takes a different route than planned. For example, a spoofed GPS signal can trick the ship into believing that it is in the center of the canal when, in fact, it is sailing towards the bank. In canals, a minor deviation can result in grounding. Analysis also considered the role of ECDIS, which relies on GPS information. If ECDIS is fed with erroneous information, the ship's navigation system might not be able to detect shallow water, and grounding becomes more likely (Sakar et al., 2021).

2. Collision with Locks or Banks

Collision with canal banks or locks is yet another dangerous accident that the STPA-Safety/Security analysis exposed. Canals typically require precise maneuvering, especially when going through locks or sharp turns. Communication jamming is the UCA for this accident. In this accident, a hacker disrupts communication between the ship and the shore-based control center, especially during safety-critical maneuvers such as going through locks. For example, if the ship is unable to receive real-time instructions from the control center, it may fail to alter its speed or direction, thereby colliding with the lock gates or the canal banks. The analysis also exposed the susceptibility of wireless communication systems, such as 4G or satellite communications, that are typically used in remote-controlled ships. A denial-of-service (DoS) attack on such systems would render the ship incommunicado, increasing the risk of a collision (Yousaf et al., 2024).

3. Loss of Propulsion Control

Loss of propulsion control is a serious accident that can be experienced in case a ship’s propulsion units are compromised. The STPA- Safety/Security listed unauthorized access to thruster controls as the central UCA that can lead to this type of accident. In this scenario, a hacker infiltrates a ship’s propulsion system, either through a wireless network or by attacking weak points in a ship’s software. The hijacked ship can be commandeered by a hacker, who can override instructions sent to thrusters, leading to power failure or lack of ship maneuverability (Longo et al., 2024). The scenario is very unsafe in canals, as ships primarily utilize thrusters in their maneuverability, e.g., making turns in a narrow channel space. The analysis also accounted for a situation in which a hacker commandeers a ship’s ECUs, which can lead to quick speed alterations or directions, which can lead to accidents.

4. Safety and Security Constraints Integration

The STPA- Safety/Security not only identified accidents and corresponding UCAs but also integrated safety in addition to the security constraints in order to take into account overall risk. For example, the analysis accounted for cities' proximity to canals, which elevates the risk of a cyberattack due to publicly accessible tracking web pages with AIS. Such web pages facilitate hackers in tracking ship travel as well as in staging ambushes at weak points in crossing canals, e.g., in lock operation and in close maneuvering (Soner et al., 2024). The analysis also accounted for prioritized monitoring in real time detection in case of anomalies in order to foresee risks uncovered. For example, incorporating inertial navigation systems (INS) with GPS will facilitate redundancy in order to facilitate ship position crosschecking and detection of spoofing.

Step 2: Threat Analysis at the Component Level

Upon identification of risks in terms of security, the second step is analyzing probable impacts that can be caused by a MASS ship of level 3 as a threat in case it is attacked in a canal. The consequence of a cyber-attack is quantified in terms of the amount of physical damage that can be caused by a ship in a canal.

Step 3: Unsafe Control Actions (UCAs)

Identification of unsafe control actions (UCAs) is crucial in determining why a failure in a ship's systems or a cyber-attack can cause unsafe operation in transiting canals. Each unsafe control action is a condition in which a control action is not implemented correctly, implemented at a wrong time, or not at all, leading to accidents. The following is a technical explanation of UCAs identified in this study as shown in Table 2 and Table 3.

Table 2 Critical Components and Threats

Component	Vulnerability	Example Threat
Navigation Systems	GPS/AIS spoofing	False coordinates mislead the ship, causing grounding.
	ECDIS manipulation	Incorrect chart data increases grounding risks in narrow channels.

Communication Systems	4G/5G network jamming	Loss of real-time navigation during lock transits, leading to collisions.
	Sensor/camera compromise	Failure to detect obstacles, increasing collision risks.
Propulsion Systems	ECU hacking	Unauthorized thruster control disrupts maneuverability in tight bends.
	Azimuth thruster override	Sudden loss of steering, causing collisions with banks.
Canal Infrastructure	Lock control system sabotage	Trapped vessels due to malfunctioning lock gates (e.g., disrupted water management).
Publicity of Data	Public AIS tracking exploitation	Hackers time attacks using real-time ship position data.

1. GPS/AIS Spoofing

GPS/AIS'S spoofing is a condition in which a hacker manipulates ship navigation data, presenting fictitious coordinates to the GPS or AIS. The ship can be diverted into a wrong course, particularly in narrow canals, in which case slight deviations lead to grounding or collision with bank canals. In the bulker *Rosco Poplar* incident (2022), fictitious GPS coordinates made a ship ground in in the Great Barrier Reef. Such a condition is very dangerous because ship personnel or faraway controllers are unlikely to realize in a quick manner that fictitious input is ongoing, leading to a time lapse before rectification.

2. Communication jamming

Communication jamming is a condition in which a ship is barred from communicating in a live manner with a shore-based control room, particularly in critical lock transits. A 4G/5G network DoS attack can jam updates in navigation instructions. In a bulk carrier *Glory Amsterdam*, which ran aground about 1.6 nm north of the German North Sea Island of Langeoog following a disruption in communications in a lock approach by a DoS attack, a high level is observed in which lock operator-coordinated turns are crucial in order to navigate canals in a secure manner.

3. Thruster Override

Thruster override is a condition in which a hacker infiltrates a ship's propulsion system in a manner not allowed, overruling instructions in thruster or power train. The ship can experience a quick propulsion failure or lack of maneuverability, particularly in bends in canals or waterlogged canals. For example, Ro-Ro cargo vessel *Mazarine*, grounded on Wolf Rock, off Land's End, UK on 10 July 2023. Though less common (10% frequency), its consequence is severe as it can render a ship unsafe in confined water spaces.

4. Lock System Sabotage

Sabotage in lock systems is a situation in which a hacker infiltrates into the automated lock control system, stopping gate operation or water level management. The vessels are detained in a lock, resulting in congestion and increasing collision hazards. For instance, a hypothetical attack on a

Grand Union Canal lock system can lock multiple vessels in a lock, stopping canals' operation. Such a UCA is more threatening in congested canals, as lock operation is vital in maintaining vessels' flow.

5. Sensor/Camera Combination

Sensor/camera compromise is a condition in which a ship's sensors or cameras are degraded or compromised, making its detection of obstacles as well as other ships difficult. Sensor/camera compromise can lead to allisions (collision with static structures) as well as collision with ships. Sensor/camera compromise is particularly important in narrow waterways, as detection of obstruction is important in order to navigate appropriately.

Table 3 UCA causes and consequences, generated from STPA Safety/Security

UCA	Scenario	Cause	Consequence
GPS/AIS Spoofing	Spoofed coordinates during canal transit.	Hacker manipulates GPS/AIS data using tools like HackRF.	Grounding or collision with banks
Communication Jamming	DoS attack during lock approach.	Hacker disrupts 4G/5G networks, blocking real-time navigation updates.	Collision with lock gates
Thruster Override	Unauthorized access during tight maneuvers.	Hacker gains control of propulsion systems via ECU vulnerabilities.	Loss of propulsion, leading to collisions (10% of incidents).
UCA	Scenario	Cause	Consequence
Lock System Sabotage	Hacking automated lock controls.	Hacker infiltrates lock control systems, disrupting gate operations.	Vessels trapped in locks, causing delays.
Sensor/Camera Compromise	Tampering with obstacle detection.	Hacker disables or manipulates wireless sensors/cameras.	Allisions with fixed objects.

Step 4: Identify threat scenarios likelihood

The Ship Attack Threat Model for Canal Transits is a formalized methodology towards understanding in which manner a cyber-attack can cause a disruption in secure operation in remotely operated ships in canals. The model is categorized into three broad categories: Canal Wireless Attack Vectors, Attack Enablers, and Operational Context, each in turn categorized into discrete scenarios and threats. In the following discussion, The authors describe in great detail the diagram as well as its scenario.

The threat model for canals' transits is grouped into three categories: Canal Wireless Attack Vectors, Attack Enablers, and Operational Context. Each category represents a critical element in the cybersecurity threat that confronts remote-controlled ships in canals, which collectively paints a picture that can be used in understanding as much as in countering these risks as shown in Figure 1, the data is collected from the accidents investigation reports and validated through experts.

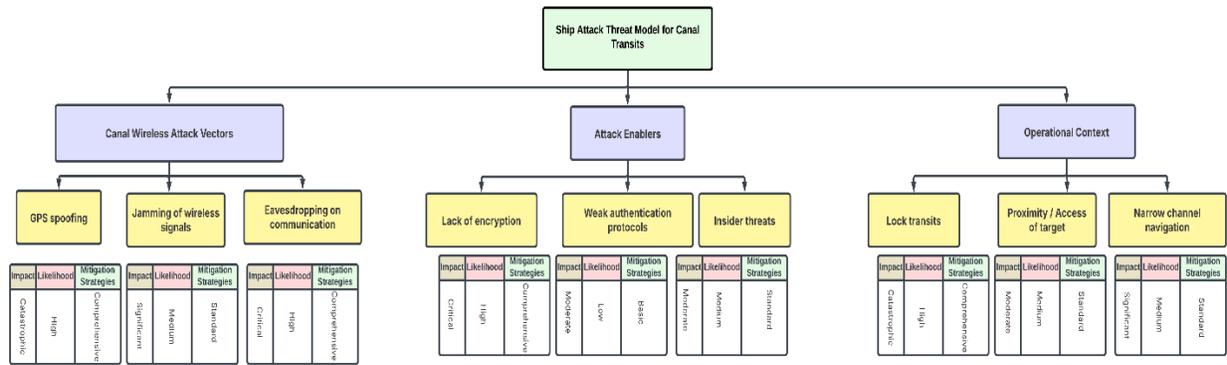


Figure 18 Categories of ships cyber-attack during canal transit
Source: Developed by authors based on STPA and Delphi outputs

1. Attack Enablers

The first primary category in the model is on resources and tools that enable cyber-attack. The hackers take advantage of specialized software, i.e., Kali Linux, for packet injections and penetration testing in order to take advantage of shipborne systems' vulnerabilities. In addition to software, hackers take advantage of specialized domain awareness regarding marine systems as well as devices such as HackRF in order to do GPS spoofing or signal modification with software-defined radios (SDRs). Low-end devices, i.e., SDRs, also enable hackers in order to do wireless-based attacks with minimal monetary costs. The above facilitators are at the foundation of the threat model because these are the resources with which hackers are able to do advanced attacks on distant-controlled vessels.

2. Canal Wireless Attack Vectors

Canal Wireless Attack Vectors in the model represents targeted attack vectors that impact ship systems in transiting canals. The largest threat is that of GPS/AIS spoofing, wherein a hacker corrupts a ship's GPS or AIS data, making it deviate from its intended route. Grounding or collision with bank can be a consequence, particularly in narrow water bodies. Communication jamming is another critical threat wherein a DoS attack on a ship disrupts its communications with shore-based control. It is particularly threatening at critical points, as in lock transits, wherein live coordination is essential. The third critical threat is that of thruster override, wherein a hacker accesses a ship's propulsion system in a non-approved means and overrules instructions on thruster or engines. The consequence can be a quick failure in propulsion or maneuverability, which can lead to enhanced collision risks. The above attack vectors depict weak points in ship-based remote control in canals, wherein accurate navigation as well as communications are essential in order to navigate in a secure way.

3. Operational Context

The third primary category in the model represents operational surroundings in which attacks occur, which also involve ship location that hackers with reference to target location and the operation conditions - response time as well as Target Accessibility. In Operation Status - Reaction

Time, ships are in a high-risk position in lock transits, in which high-coordinate demands create a high-risk situation. A cyber-attack at this level, either in terms of GPS jamming or spoofing or locks operations manipulating, can be critical in its impact, with possibilities that can involve collision with lock gates. The Proximity/Access category examines ways in which physical access is adopted by hackers. Canal facilities' accessibility, i.e., lock accessibility, is at a high level because hackers can have direct access over control systems. Disguising as a passenger or through pleasure boats approaching ships in a wireless manner are at a moderate level because hackers can attain target proximity. Disguising as a drone (Snoopy Drift), on the other hand, is a low-risk strategy because technical limitations as well as complexity in executing drone-based attacks are involved.

Step 4: Assessing the Probability of Threat Scenarios

The identification of threat scenario likelihoods is a critical step in understanding the risks faced by remote-controlled ships during canal transits. Building on the UCAs identified in Step 3, this step evaluates the probability of each threat scenario using expert input and the Fuzzy-AHP. The authors analyzed the potential opportunities and harm a hacker could inflict by targeting and compromising Degree 3 autonomous ships while navigating through canals based on the expertise opinions whose qualifications, as outlined in Table 1, include expertise in ship accident investigation, maritime cybersecurity, and ship simulation, ensuring a comprehensive evaluation of the risks.

Logical Scenario: GPS Spoofing During Lock Transit

The Delphi method was systematically implemented through three iterative rounds to validate and refine threat assessments, following established protocols for expert consensus-building (Dalkey & Helmer, 1963). In Round 1, maritime cybersecurity specialists ($n=5$; Table 3) independently evaluated threat scenarios generated by STPA-Sec. Round 2 anonymized and aggregated responses using Equation (3)'s defuzzification to resolve discrepancies, while Round 3 achieved consensus (Kendall's $W > 0.7$) on final threat weights. This process directly informed the Ship Attack Threat Model's three-tiered structure: (1) Attack Vectors (e.g., GPS spoofing), (2) Enablers (e.g., HackRF tool accessibility), and (3) Operational Context (e.g., lock transit proximity). The model quantified scenario risks via F-AHP weights (Table 4), with expert-derived adjustment factors applied to account for canal-specific conditions (e.g., 23% risk escalation for cyber-physical attacks during lock operations). Cross-validation against IMO GISIS incident data (2020–2024) confirmed model robustness, particularly for high-weight threats like spoofing ($R^2 = 0.82$ between predicted and actual incident frequencies).

An exemplary application of this threat model is a lock transit GPS spoofing attack. In a lock transit case, a spoofer utilizes a HackRF device in order to impersonate a ship's GPS coordinates as it is approaching a lock. The ship is given false coordinates, which direct its navigation away from its intended course. The consequence is a collision with a lock gate, which results in massive destruction on ship as well as lock infrastructure. The scenario fits into the category of Lock Transit: High Risk (0.173), which obviously demands effective countermeasures. In order to

counteract this threat, having redundant navigation systems available, i.e., inertial navigation systems with a combination with GPS, can be effective in detecting and correcting attempts at spoofing. Secure communications channels can also be encrypted, as can ship system access. The research identified that target location monitoring via AIS is a vital component in determining target location-based probability of a cyber-attack. The highest weights included Port Entry (0.130), Berth (0.124), Canal (0.110), as these are more susceptible due to increased complexity and confined spaces. The reverse is true with Coastal Navigation (0.062), as it is identified as lowest in terms of threat. Open seas have more room in which remedial measures can be taken as well as having a minimal number of obstacles. Similarly, reaction time in terms of operation status varied with location, with shortest reaction time with Port Entry (0.176), as high traffic as well as high coordinating requirements are involved. Canal (0.041), as well as Coastal Navigation (0.073), are also lower risks due to slower speeds and the reduced obstacles.

The target's accessibility and proximity also significantly influenced the likelihood of cyber-attacks. Access to Canal Facilities (0.131) was identified as the highest risk, as hackers could physically access critical infrastructure, such as locks or control systems. Impersonating a Passenger (0.121) and Pleasure Boat Approach (0.111) were deemed moderate risks, as these methods allow attackers to gain proximity to the ship and exploit wireless vulnerabilities. In contrast, UAVs (Snoopy Drone) (0.035) were ranked as the lowest risk due to the technical challenges and limitations associated with drone-based attacks.

The findings shown in Table 4 were further validated through IMO GISIS, which highlighted the prevalence of grounding and lock collisions in canal environments. These incidents are often linked to navigation errors and communication failures, reinforcing the relevance of the identified threat scenarios. For example, A crude oil tanker, the Ceres I, collided with another tanker off Malaysia in the South China. The collision caused significant damage to both ships. While Malaysian authorities cited technical difficulties as the reason for the incident, analysts believe that the Ceres I was deliberately transmitting a false location.

Table 5 Weight of Threat Scenario

Category	Subcategory/Scenario	Weight/Risk Score (Eigenvector)	Consistency Check (CR < 0.1)
Logical Scenario	GPS Spoofing During Lock Transit	0.173	Valid
Target Location Monitoring	Port Entry	0.130	Valid
	Berth	0.124	Valid
	Canal	0.110	Valid
	Coastal Navigation	0.062	Valid

Response Time in Operational Context	Port Entry	0.176	Valid
	Canal	0.041	Valid
	Coastal Navigation	0.073	Valid
Target Accessibility and Proximity	Access to Canal Facilities	0.131	Valid
	Impersonating a Passenger	0.121	Valid
	Pleasure Boat Approach	0.111	Valid
	UAVs (Snoopy Drone)	0.035	Valid

4- Conclusion

The study reiterates the primacy of cyber resiliency in canal environments for operation of remote-controlled Maritime Autonomous Surface Ships. The study indicates that despite new technologies allowing such a possibility of operation in an effective manner, such technologies expose such ships to a great risk of cybersecurity attacks. With little knowledge of operation of a ship and in possession of cheap toolkits such as HackRF and Kali Linux, such criminal entities can exploit navigation, communication, and drive system vulnerabilities in such a manner as to unleash severe destruction. The study reiterates that in relation to the field of cyber security, there is an infancy of experience and understanding among experts and maritime staff, which is a congenial ground for a hacker to operate for a lengthy period. This is especially dangerous in canal navigation, in which narrowness and complexity of canals increase the scale of resulting cyber-attacks.

The research establishes a weighted hierarchy of canal-specific cyber threats, with GPS/AIS spoofing (0.173 weight) and communication jamming (0.131) emerging as critical risks during lock transits. These findings validate and extend prior maritime cybersecurity studies by quantifying threat severity in confined waterways through expert-calibrated F-AHP weights.

The novel integration of STPA-Security with Delphi-validated F-AHP addresses the research gap in maritime cyber-risk assessment identified. The three-round Delphi process (Kendall's W = 0.78) ensured that the component-level threat analysis (Table 1) reflects both technical vulnerabilities and operational realities reported by maritime practitioners.

The study's findings yielded into three targeted cybersecurity measures for autonomous ships operating in canals and narrow channels. First, redundant navigation architectures combining inertial systems with satellite positioning provide real-time spoofing detection through continuous data validation. Second, hardened communication protocols with dynamic encryption prevent jamming attacks during critical maneuvers such as lock transits. Third, segmented thruster control systems with isolated network domains and runtime integrity checks minimize the impact of potential overrides. These solutions directly address the high-risk scenarios identified in our analysis while accounting for the unique spatial constraints and operational requirements of confined waterways. Unlike generic cybersecurity approaches, the proposed measures specifically

balance threat mitigation with the need for uninterrupted navigation precision in these challenging environments.

This focused implementation pathway demonstrates how theoretical risk assessment can directly inform maritime cybersecurity practice. The countermeasures align with emerging industry standards while providing actionable guidance for ship designers and canal operators seeking to secure next-generation autonomous vessels. By bridging the gap between academic risk models and operational realities, the study offers a template for context-aware cyber protection in critical maritime infrastructure.

Several key learnings can be extracted from this study. One is an urgent call for enhanced cybersecurity literacy and education among seafarers in a position to detect and counter cyber threats. Secondly, though current technologies and legislation provide a certain amount of security, compulsory regulations in all regions must be made for there to be standard and secure practices of cybersecurity. Lastly, port facilities and canal operators have a duty of care in taking proactive measures, such as authenticating wireless communications and exploring using military-grade technology, in securing critical infrastructure against cyber-attacks.

While it is a valuable contribution, there is a set of limitations. Hypothetical scenarios and IMO GISIS data limit the potential for all outcomes being verified in an empirical sense. The Delphi process, although powerful, is potentially biased due to being among experts. This can be countered by extending the panel of experts so it is more representative of stakeholders. The study is on channels and canals, and outcomes may not generalize in other regions due to different environmental and regulatory contexts.

Future research should take into account various directions for extending this study. One is necessary for analyzing technology improvements, for instance, on intrusion detection systems and anomaly algorithms, in an effort to enhance MASS cybersecurity. Other studies must take on establishing and enforcing MASS-wide cybersecurity standards so practices can be made uniform in regions. Other case studies of actual cyberattacks on autonomous ships, in more detail, can provide insights on current countermeasures' efficiency and identify directions for optimization. Finally, future research should investigate the role of human factors, such as operator training and decision-making, in preventing and responding to cyber-attacks.

In conclusion, the findings of this study demonstrate the importance of integrating cybersecurity into the design and operation of remote-controlled ships, particularly in canal environments. By combining STPA- Safety/Security and Fuzzy-AHP, the study provides a valuable methodology for ongoing monitoring, review, and mitigation of cybersecurity threats. However, as the maritime industry continues to adopt autonomous technologies, it is essential to regularly update the model to reflect technological advancements, emerging threats, and changes in operational environments. This study serves as a foundation for future research and policy development, contributing to the safe and secure operation of autonomous ships in an increasingly digitalized maritime industry.

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The Integration of ArcGIS Drone2Map with ArcGIS Pro Software to Solve the Miss Alignment in Processed Drone Data to Extract Shoreline

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المستخلص

يُعرف خط الساحل بأنه الحدود الفاصلة بين البحر واليابسة، ويؤدي استخراجُه بدقة دورًا بالغ الأهمية في القيمة الاقتصادية والبيئية للمناطق الساحلية، خاصةً في ظل التأثيرات الكبيرة للاحتباس الحراري وارتفاع مستوى سطح البحر. في الآونة الأخيرة، يُستخدم الاستشعار عن بعد بالأقمار الصناعية على نطاق واسع لمراقبة البيئة.

تُظهر الصور عالية الدقة التي توفرها الطائرات المسيّرة اليا تحسنًا كبيرًا في دقة استخراج خط الساحل وتفصيله الدقيقة مقارنةً بالبيانات التقليدية المستمدة من الأقمار الصناعية. تعتمد الموثوقية والجودة في تقنيات الاستخراج المعتمدة على الاستشعار عن بعد على عدة عوامل مترابطة. على سبيل المثال، تُعد الصور عالية الدقة ضرورية لنوع وجودة البيانات المدخلة المطلوبة للتعرف الدقيق على المعالم على طول خط الساحل. علاوة على ذلك، وعلى الرغم من الدقة العالية، فإن العوامل البيئية المتغيرة مثل الإضاءة أو الغطاء النباتي قد تؤدي إلى تدهور جودة صور الطائرات المسيّرة، ما يقلل من دقة تحديد خط الساحل.

المعالجة الدقيقة لصور الطائرات المسيّرة أمر ضروري للحفاظ على دقتها العالية. توفر حزمة ArcGIS أدوات قوية مثل Drone2Map و ArcGIS Pro لمعالجة الصور، سواء كانت مأخوذة من الطائرات المسيّرة أو الأقمار الصناعية. ومع ذلك، تم رصد انحراف ملحوظ بين البيانات المُعالجة والخريطة الأساسية عند استخدام Drone2Map في المعالجة. وقد تم استخدام أداة ArcGIS Pro (Reality Mapping) لتقليل هذا الانحراف إلى بضعة سنتيمترات، وهو ما يُعد نتيجة مقبولة لإنشاء النموذج الرقمي للسطح (DSM) من صور الطائرات المسيّرة.

Abstract

Shoreline is defined as the boundary between sea and land, and its accurate extraction plays a crucial role in both the economic and ecological value of coastal areas during the significant impacts of global warming and sea-level rise. Recently, satellite remote sensing is widely used for environmental monitoring.

High-resolution imagery provided by drones shows great improvement in accuracy and subtle variation of details of shoreline extraction compared to traditional satellite data. Reliability and quality under different remote sensing-based extraction techniques rely on several interrelated

factors. For example, High-resolution photography will be necessary for the kind and caliber of input data needed for precise feature recognition along the shoreline. Furthermore, despite the increased resolution, shifting environmental factors like lighting or vegetation cover may cause drone-UAV picture quality to deteriorate, decreasing the precision of coastline delineation.

An accurate processing for drone imagery is critical to maintaining the high-resolution drone imagery. ArcGIS package offers a powerful tool, such as Drone2Map and ArcGIS Pro, to process image whether it delivered from drone or satellite. Unfortunately, the significant shift between processed data and basemap has been observed when Drone2Map has been used in the processing. The reality mapping tool in ArcGIS Pro has been used to decrease the shift to a few centimeters which is acceptable result to create the Digital Surface Model (DSM) from the drone Imagery.

Keywords: Drone, GCPs, High-Resolution, ArcGIS, Drone2Map.

1- Introduction

More than 50% of the world's population lives along coasts and rivers mouths, relying extremely on natural resources and the environment for their life (Quang et al., 2021). Coastal regions are important for multiple fields such as coastal management, environmental monitoring, and economic development, including transportation and tourism (Tegar & Saut Gurning, 2018). However, the coastline's dynamic spatial and temporal variation is a significant concern due to erosion and accretion threats (Tercan & Dereli, 2021). Coastal zone management is a critical task in sustainable development and environmental protection. Due to global warming, coastal zone monitoring, and extraction of shorelines is an essential mission. The shoreline is defined as a line of contact between land and water body (Kafrawy et al., 2017).

Drones can capture very high-resolution imagery up to a centimeter or millimeter by flying close to an area of interest and capturing highly detailed images. In addition, drones are more available and versatile because they can fly under cloud cover and sometimes can also be deployed quickly compared to satellite systems. Furthermore, the advances in Unmanned Aerial Vehicles (UAVs) provide high-quality images and real-time data processing, which enhance how accurately shorelines are extracted compared with satellite imagery (Phiri et al., 2020).

Manual digitization is a shoreline extraction technique in which human interpretation plays a crucial role in geographic data analysis. The manual digitization approach will recognize shorelines from very high-resolution images provided by UAV systems among other sources for vector outputs to ensure the accuracy of shoreline or land-water boundary delineation. While remote-sensing methods enable efficient data handling, the complexity of local geography often needs human involvement to apply automatic processes, therefore, traditional methods are still very relevant in coastal studies (Colak et al., 2019). UAV technology has revolutionized remote sensing, particularly in coastal research. Drones provide high-resolution imagery and sensors, enabling quick and cost-effective acquisition of large aerial datasets. This is crucial for observing shoreline and vegetation changes. Technology allows researchers to create detailed Digital Surface Models (DSMs) and RGB orthophotos, enhancing the analysis of coastal geomorphic features. For

instance, UAV surveys have made it possible to quantify exposed sandy regions and plant cover, which has revealed solutions for ecosystem health and the efficacy of the restoration methods involved (Kemarau et al., 2024). Second, coastline extraction is improved for greater accuracy and dependability in coastal regions by combining conventional manual digitization with automatic picture categorization in GIS. As this technique has developed, the UAV has become an essential component of the most recent advanced remote sensing as shown in Table 1.

Table 6. Advantages of Drone Imagery in Shoreline Extraction.

Advantage	Description	Source	Year
Higher Resolution	Drone images capture detailed features of the shoreline, enhancing the clarity and accuracy of shoreline mapping.	National Oceanic and Atmospheric Administration (NOAA)	2022
Cost-Effectiveness	Deploying drones can be more cost-effective than traditional aerial surveys, allowing for more frequent data collection.	U.S. Geological Survey (USGS)	2023
Flexibility and Accessibility	Drones can reach places that conventional surveying techniques would find hazardous or challenging, such as rocky or unstable shorelines.	International Society for Photogrammetry and Remote Sensing (ISPRS)	2023
Real-Time Data Collection	Drones present real-time visual data, allowing for immediate analysis and making decisions in shoreline management.	Environmental Protection Agency (EPA)	2022
Environmental Monitoring	Drones help observe changes in coastal environments over time, providing crucial data for conservation efforts.	National Geographic Society	2023

Drone in remote sensing relies on the basic set of practices concerning data quality, ethics, and collaboration. Researchers should adhere to the legal framework concerning licensing, airspace, permissions, and privacy (Kutynska & Dei, 2023). Privacy concerns should be addressed by nonidentification and data security. Sensor and software limitations should be critically reviewed/evaluated to avoid “black box” solutions that are not duly validated (Lucieer et al., 2013). Standardized protocols for data acquisition, using checklists and flight planning, ensure the quality and repeatability of data (Nex & Remondino, 2014).

ArcGIS Drone2Map plays a crucial role in drone data processing, and it is essential to create DSM for the interested area then, using that surface to extract accurate shoreline.

Material, Study Area, and Methodology

This study focuses on a coastal area of Coronation Park located north of Lake Ontario in Canada. Two datasets were collected: high-resolution images captured by P1 camera on a small UAV on 22 October 2022. The projection used is Universal Transverse Mercator (UTM) zone 17N, with

EGM96 as the geoid for elevation, and the World Geodetic System (WGS) 1984 as the ellipsoid and datum, as shown in Figure 1.



Figure 1. Area of Interest. Credit: Google Pro.

Drone data was collected as raw data of 504 images that need to be processed to use in shoreline extraction. Processing has been done using Drone2Map software to produce the DSM as shown in Figure 2.

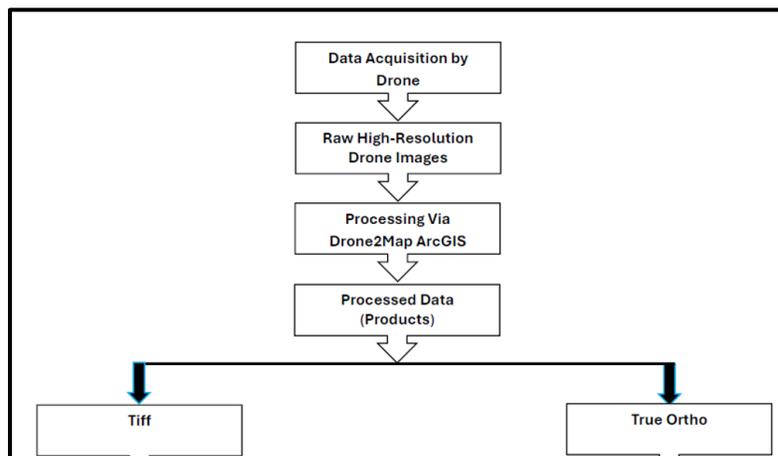


Figure 2. The Theoretical Concept of Drone Image Processing.

Combination of Tide and Seiches Effect on Lake Ontario

The Great Lakes are a chain of five connected freshwater lakes located in the North American region. These lakes include Lake Ontario which is the study area in this paper. The nature of the lakes is extremely large and is considered a major part of the entire region. However, in contrast to their size and sea-like area, the Great Lakes do not have tidal shifts as compared to other oceanic coasts. Although the Great Lakes do not have normal, so-called classic tides, there is a good deal that is close to tides in what are called seiches. It is probably more usefully viewed as the height of the water column displaced due to the combined effects of all seiche and tidal

modes. When this height is multiplied by some appropriate area it gives the total volume of water involved. The logarithmic meaning value of this measure is approximately 10 cm for Lake Ontario which is not considered a significant value to shift shoreline horizontally (Trebitz, 2006).

2- Software Packages

Multiple tools have been employed in this research, including the ArcGIS packages that are provided by Esri company, such as ArcGIS Drone2Map, Arc Map, and the advanced ArcGIS Pro full package.

2.1 The ArcGIS Drone2Map

ArcGIS Drone2Map is an application that converts raw data imagery from drones into worthy information products in ArcGIS software. It has become more accessible and convenient for generating 2D and 3D products with features and areas that may be hard to access. In addition to monitoring changes in the environment, the impact of natural disasters is also monitored. ArcGIS and ArcGIS Drone2Map possess other capabilities that assist users in revealing hidden insights into drone imagery. ArcGIS Drone2Map advantages include the following:

- a- Dealing with big data with time reduction.
- b- Building information images that assist decisions rapidly.
- c- Independence of third parties for mission-critical data gathering.
- d- Reducing costs that acquired expensive aerial image processing services.
- e- Enabling a pilot to quickly check his data for the first time.
- f- Applying the correct defaults based on its detection for sensors.
- g- Being considered an all-in-one application for image capturing, processing, and analysis.
- h- Rapidly figuring out the correct settings and adjusting them.
- i- Including automatic defaults that assist the user in quickly building essential information products for the project(Esri ArcGIS Co., 2024).

In recent years, Drone2Map became almost the most common drone image processing software due to its superior performance compared with other commercial software such as Agisoft Photoscan and Pix4D. Many studies revealed the capability of photogrammetry and computer vision in UAVs to recognize the products that construct 3D geometry. The evaluation of the output products was conducted using different visual and statistical metrics. While comparing in terms of visual data, a vertical profile was generated over other features in which Done2Map was able to create a more accurate DSM over the tree canopy while the Agisoft Photoscan and Pix4D software at the same time had failed, which can be cleared to be considered as the drawback in point cloud generation. Even on the elevated road, Drone2Map was able to generate the proper elevation profile (Tyagi et al., 2022).

3- Drone Data Processing

Drone images have been processed using Drone2Map by uploading the captured high-resolution drone images. The project was created, and pre-processing adjustments such as camera calibration, georeferencing, and checking the parameters of final products were made. Once

the adjustment is applied, it is saved in the project option and ready to be used during the processing, as shown in Figure 3. Running the Drone2map tool to process the high-resolution images delivered by the P1 camera on the drone will take longer processing time depending on the machine performance used, such as CPU or GPU, in addition to the quality required to generate the desired products, for example, DSM or True Ortho products.

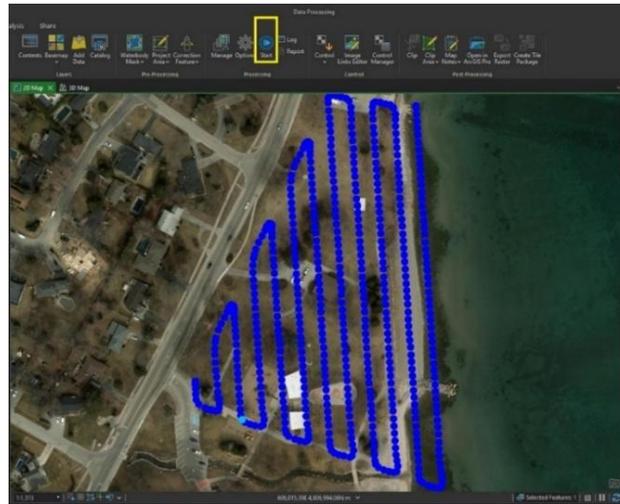


Figure 3. Data Adjustment Before Processing Using Drone2Map.

3.1 Data Processing Report

Drone2Map reconstructs drone imagery into desired products. The processing report offers essential information about the project, including details on quality and accuracy, as well as a summary of the defined processing options. The processing took more than 14 hours, indicating 6 mm as a resolution of the captured data and the number of images that have been processed, as shown in Table 2.

Table 7. The Processing Summary.

Project Summary	
Project Name	FINAL DATA PROCESSING MELIGY57
Processed On	12/5/23, 06:58 AM
Camera Model	DJI ZENMUSEP1
Images	504 out of 504 images calibrated
Project Area	0.056 km ² / 5.644 ha / 0.022 sq. mi. / 13.947 acres
Ground Resolution	0.006 (m)
Processing Time	14h:32m:23s

Table (2) also shows essential information about the project, such as the project name, date, and camera model. All the project images were processed and calibrated successfully, and no problems occurred due to the project configuration. If images are not calibrated, the interesting images should be double-checked and investigated for the causes of the problem.

Drone2Map utilizes photogrammetry to process the project's imagery. The software identifies neighboring images that share overlapping features and creates tie points between them. This process is repeated thousands of times throughout the project, establishing a network of connections (solution points) that Drone2Map uses to align the images accurately. The project reconstruction is proper when there are more tie points and solution points.

3.2 Images Positions Uncertainty

The adjustment of image positions graphic shows the visualization of shifts that occurred to the center point of the adjusted images. The blue points reveal the imagery locations of the initial position, and the green points show where they were reprojected. A significant shift between the points indicates a poor positioning system in data collection.

Figure 4. visualizes the shifts between blue and green points, which is the shift between the initial and reprojected positioned images. The accuracy of the positioning system will be checked compared to the ground truth of this mission.



Figure 4. Image Positions Adjustment.

3.3 Postprocessing Results

Although geodetic control points (GCPs) were used in collecting the datasets, they were not applied in the processing. However, by the end of processing, the processed data was validated by extracting coordinates of the GCPs positions from the processed data and comparing them to the original GCPs to check the matching and accuracy between the base map and the processed data. The difference in the horizontal component demonstrates a significant shift of more than one

meter, as demonstrated in Table 3. This significant uncertainty requires some editing and adjustment.

Table 8. The Shift Between Original and Processed GCPs.

GCPs	Original True GPCs		Processed Data GCPs
pt3	605948.38	4807222.24	605,948.57 E 4,807,223.19 N
pt4	605934.91	4807159.49	605,934.76 E 4,807,160.1 N
pt5	605890.27	4807098.74	605,889.91 E 4,807,098.68 N
pt6	605932.1	4807020.63	605,932.07 E 4,807,020.13 N

To visualize the mismatching, Figure 5. displays the shift between the base map and the processed images without applying the original GCPs.

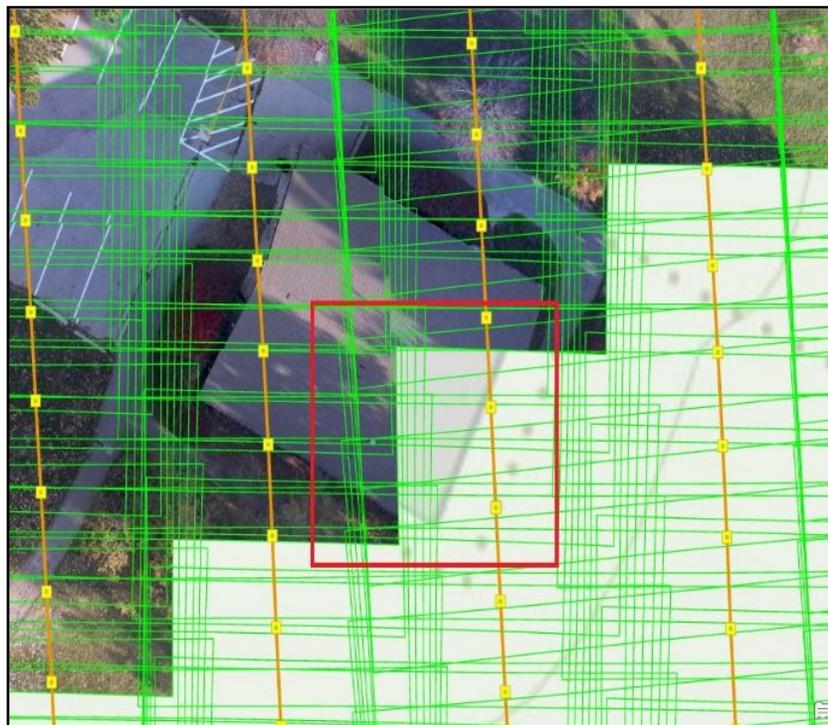


Figure 5. The Mismatching Between the ESRI Base Map and Processed Images.

Hence, the solution should exist in Drone2Map because its back end was built on the PIX4D in the past, and nowadays, its back end has been built on the German software nFrames. However, an alternative solution has been found to correct the mismatching and complete the processing phase through the ArcGIS Pro with a Reality Mapping extension. This extension is the same as Drone2Map, but the ArcGIS Pro can deal with big data, as indicated in Figure 6.

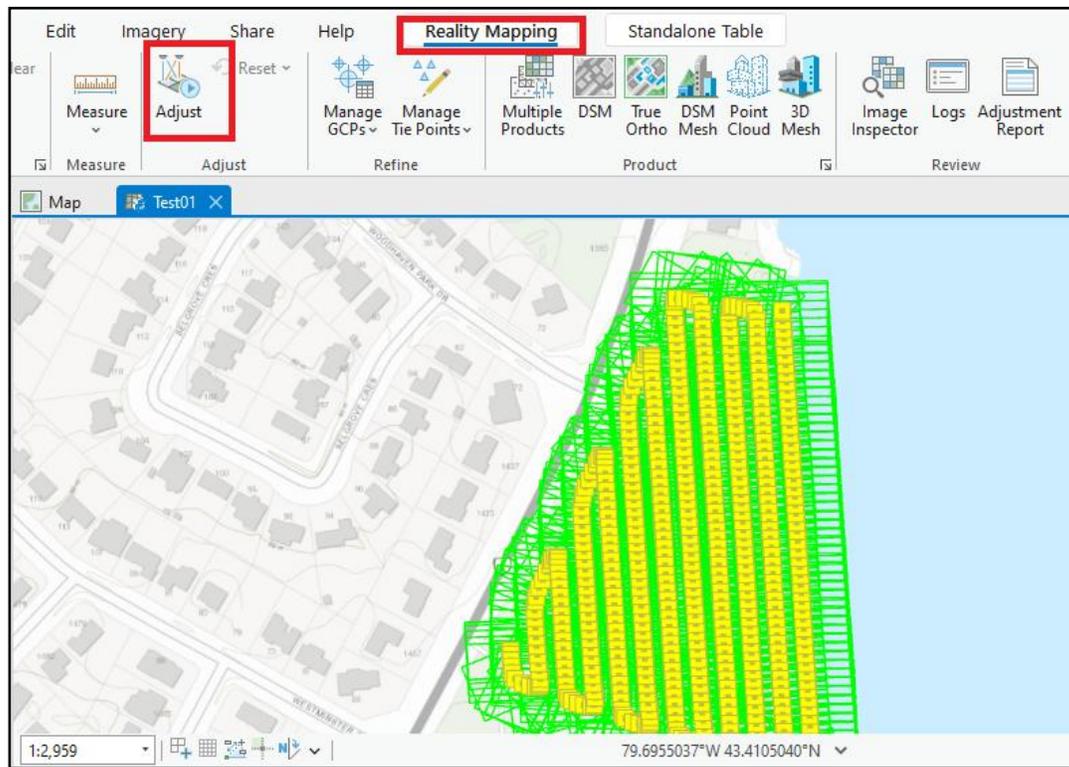


Figure 6. Reality Mapping Extension.

To correct this shift, two methods were found as follows:

- a- To align the processed images with the base map, attempt to adjust their positions to correct any shifts. However, this method is effective only when GCPs consistently shift at each location. Unfortunately, this approach is not suitable for the current situation.
- b- The second option is to utilize Reality Mapping to correct mismatches. This process begins with the (Adjust) function aligning the photos, defining their boundaries, computing tie points, and extracting the coordinates from the images themselves. However, the adjustment was made without using the GCPs, and manual management was made to correct the mismatches of each GCP.

The second option was applied to complete the adjustment phase, and reality mapping products were activated to create the True Ortho product and verify its accuracy and consistency.

The GCPs have not been used to assist in the adjustment because the primary purpose of the GCPs is to validate the processing results. Also, the DSM product was generated after correcting the mismatches, as reported in Figure 7.

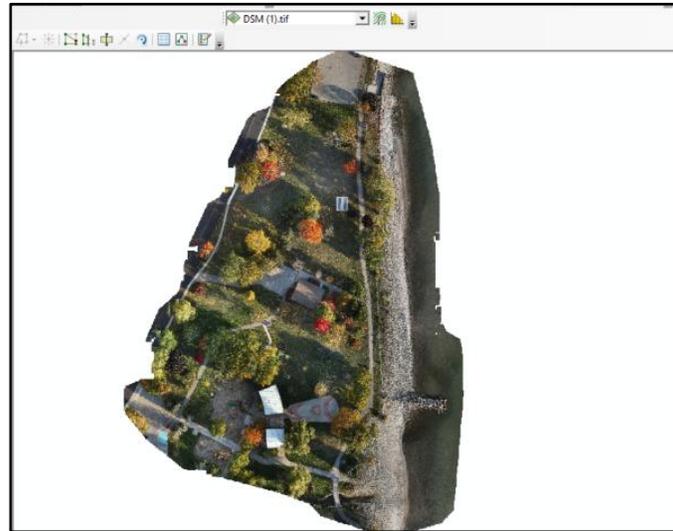


Figure 7. DSM Product from the Drone.

Additionally, an accuracy validation of the processing was employed by comparing the coordinates of the GCPs located on the DSM with the original ones. This comparison highlighted a significant improvement in accuracy. Moreover, the previous horizontal shifting has been reduced from one meter to just a few centimeters, as shown in Figure 8. and Table 4.

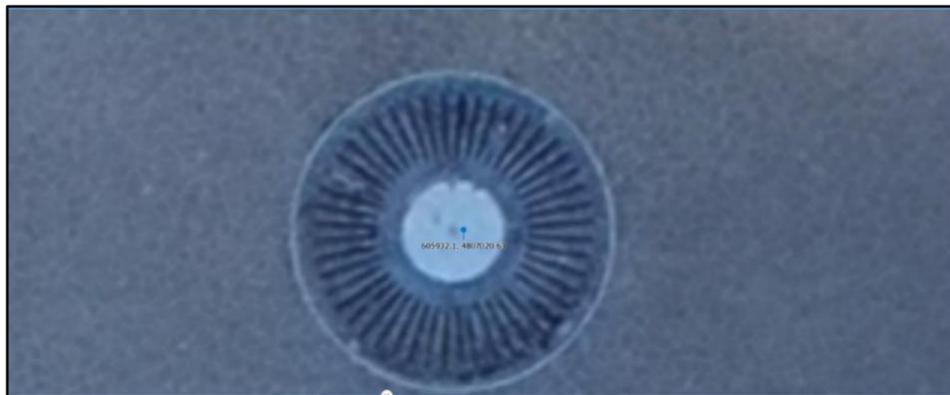


Figure 8. The Comparison Between Original and DSM GCPs.

Table 9. The Original GCPs vs. the DSM GCPs.

GCPs	Original Coordinates		GCPs	From true ortho after processing without using the original control points	
3	605948.38	4807222.24	3	605948.45	4807222.20
4	605934.91	4807159.49	4	605934.88	4807159.45
5	605890.27	4807098.74	5	605890.25	4807098.71
6	605932.1	4807020.63	6	605932.08	4807020.65

The images delivered from the P1 camera on the drone have been processed successfully and validated using the original GCPs to ensure the accuracy of high-resolution images delivered by drone. Therefore, the drone processed imagery is ready to use for shoreline extraction.

3- Conclusions

The main aim of this paper is to Solve the Miss Alignment in Processed Data from Drone in Shoreline Extraction through the integration of ArcGIS Drone2Map with ArcGIS Pro Software. First, the drone imagery has been processed using ArcGIS Drone2Map and by the end of this processing, the evaluation has been applied using the GCPs finding the shift between the processed data and the basemap. ArcGIS Pro played an essential role in figuring out this shift by reprocessing the drone data using the reality mapping tool which can decrease that shift to a few centimeters without using the GCPs in the processing as a ground truth. To conclude, validation is crucial in each phase of the processing, in addition to, the integration between several software such as ArcGIS Drone2Map and ArcGIS Pro has powerful to maintain the data accuracy.

4- Acknowledging

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The Negative Impact of Complacency on the Seafarer's Attitude and Behaviors

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المستخلص

في القطاعات الحرجة للسلامة، وخاصة قطاع النقل البحري، يُعد التراخي مشكلة متكررة وخطيرة، إذ يُعد سبباً رئيسياً للحوادث والوقائع التي تؤثر على البحارة والبيئة البحرية والموارد الاقتصادية. يهدف هذا البحث إلى دراسة الأسباب الجذرية لتراخي البحارة وتأثيره على أداء السلامة. ومن خلال اعتماد منهجية بحث مختلطة تجمع بين الأساليب الكمية والنوعية، تمكنت الدراسة من إنتاج بيانات شاملة وذات مغزى. قدمت البيانات الكمية أنماطاً كمية تتعلق بالتراخي والتوتر والرضا الوظيفي والثقافة التنظيمية، بينما تم جمع البيانات النوعية من خلال استبيان يهدف إلى التقاط وجهات نظر فريدة من البحارة. كما بحثت الدراسة كيف يختلف التراخي باختلاف نوع السفينة وظروف العمل المختلفة. وأظهرت النتائج أن اليقظة البشرية ضعيفة، وأن التراخي يحدث بشكل غير مقصود، حتى مع مساهمة التكنولوجيا - مثل أنظمة الأتمتة والمراقبة - في تحسين الكفاءة التشغيلية. لا يقتصر هذا التأثير المزدوج على تقويض السلامة البحرية فحسب، بل يزيد أيضاً من مستويات التوتر والإرهاق وعدم الرضا لدى البحارة، مما يؤثر سلباً على صحتهم النفسية والجسدية. تُسهم هذه الدراسة في الأدبيات العلمية من خلال تسليط الضوء على أهمية مراعاة آراء البحارة عند وضع استراتيجيات للحد من التراخي، وهو جانب لم يحظَ باهتمام كافٍ في الدراسات السابقة.

الكلمات المفتاحية: التراخي، السلامة البحرية، البحارة، الإجهاد، الرضا الوظيفي، الثقافة التنظيمية، الأتمتة

Abstract

In safety-critical sectors, particularly in maritime transport, where it is a major cause of accidents and incidents involving seafarers, the marine environment, and economic resources, complacency is a recurring and dangerous problem. The objective of this study is to investigate the root causes of seafarers' complacency and its impact on safety performance. By using a mixed-methods approach, i.e., a combination of qualitative and quantitative research methods, the study produced comprehensive and meaningful data. While the quantitative data provided quantitative patterns regarding complacency, fatigue, job satisfaction, and corporate culture, the qualitative data was collected through questionnaire to capture the unique views of seafarers. The study also examines the way compliance varies by vessel type and other working environments. The findings are that human watchfulness is weakened, and complacency is inadvertently created, even while technology like monitoring and automation systems improve operational effectiveness. In addition to compromising maritime safety, this double impact renders seafarers more stressed, tired and dissatisfied, and detrimental to their mental and physical well-being. The study adds to the body of knowledge by pinpointing the importance of taking seafarers' viewpoints on board while

formulating methods of minimizing complacency, something that has been broadly overlooked in existing research.

Keywords: Complacency, Maritime Safety, Seafarers, Fatigue, Job Satisfaction, Organizational Culture, Automation

1- Introduction

Across a range of safety-critical systems, such as the aviation, medical, nuclear power, military, and maritime industries, complacency continues to be a major contributing factor to accidents and incidents. (Liu, 2023; Merritt et al., 2019).

Complacency is one of the common and major problems in so-called safety-sensitive industries, most especially in the marine industry. Complacency has contributed substantially to the rate of accidents and incidents that include serious consequences for Seafarers, the marine environment, and finances. Over 80% of marine accidents are caused or influenced by human and organizational factors, highlighting the critical need for improved training, safety culture, and risk management practices within the maritime industry. (Apostol-Mates & Barbu, 2016).

2- Problem Statement

Complacency is a significant and inadequately studied element leading to accidents and safety hazards in the marine sector.

In highly mechanized, multitasking workplaces, Seafarers may develop excessive dependence on automated technologies. This results in less attentiveness, as crew members presume these systems are always trustworthy and redirect their focus to less demanding activities. The deceptive sense of security offered by reliable technology undermines situational awareness and elevates operational risk. Complacency is a significant and insufficiently studied component that contributes to accidents and safety hazards in the marine sector.

The crew often exhibits complacency due to inefficient communication, a lack of empathy, and self-interest, which reflect poor leadership. Seafarers exhibit less responsibility and attentiveness about safety protocols when their supervisors neglect to interact with their crews or articulate requirements clearly. The phenomenon of management-related complacency arises when crew members perceive that their concerns are disregarded or when operational constraints necessitate them to disregard conventional procedures. A direct threat to safety on board may be the result of disengagement and procedural shortcuts, which can be caused by inadequate management support and responsiveness.

Seafarers may experience a psychological condition of disengagement due to delayed job advancement, insufficient acknowledgment, or feelings of undervaluation. This self-induced complacency reduces their drive to remain vigilant and follow safety measures, so increasing their susceptibility to mistakes and dangerous conduct.

3- Research Aim and Objectives

The aim of this research paper is to provide insights for the:

- a) Better Maritime Safety
- b) Prevention of Loss of Life and Environmental Damage
- c) Lowering Financial Costs
- d) Enhancing the Well-Being of Seafarers as the Complacency can have a negative impact on the emotional and physical well-being of sailors.

3.1 Research Objectives

- a) Identify the root causes of complacency among seafarers.
- b) Exploring how complacency influences seafarers' behavior will help assess its impact on maritime safety.
- c) Analyze the performance consequences of complacency, investigate the impact on seafarers' well-being and job satisfaction, Attitudes and morale.

4- Research Framework and Methodology.

This study employed a mixed-methods research design, where qualitative and quantitative data were merged to gain an in-depth understanding of the causes of complacency among seafarers and its implications on maritime safety.

4.1. Research Model and Hypotheses

The research was guided by a conceptual model examining the relationship between complacency, fatigue, organizational culture, job satisfaction, and technological influence on safety outcomes. The following hypotheses were tested:

- **H1:** There is a clear correlation between levels of complacency and seafarer's fatigue.
- **H2:** Compliance behavior of seafarers is significantly influenced by organizational culture.
- **H3:** Overall work satisfaction and safety behavior suffer when one is complacent.
- **H4:** Improvements in ship monitoring systems and automation increase the danger of complacency.

4.2. Interrelated Aspects of Complacency in Maritime Safety: A Theoretical Framework

This study aimed to analyze the complex problem of job satisfaction of seafarers and to assess the influence of factors such as technological progress, organizational culture, job satisfaction, and fatigue on job satisfaction. The four hypotheses were examined shed light on different aspects of this complex organization. The initial hypothesis examines the relationship between job satisfaction and exhaustion, which confirms that cognitive functions and attention are significantly impaired by fatigue, which threatens work safety in the maritime sector. The second hypothesis examines the influence of corporate culture on compliance behavior, stating that leadership style, communication techniques, and prioritization of safety measures significantly influence the degree

of compliance by employees. The third hypothesis posits that low job satisfaction may be a result of insufficient professional development, which can lead to a negative cycle of dissatisfaction and lower-quality security services. This hypothesis is supported by research on morality and well-being. Finally, H4 examines the paradox of technological progress, emphasizing that automation and surveillance technologies can improve operational efficiency, but can also reduce human oversight and encourage overreliance on technology, thereby increasing the risk of complacency. Integrating safety measures with behavioral, organizational, and technological aspects is facilitated by combining these hypotheses. This is consistent with the International Maritime Organization's position on human factors in maritime safety and enables the implementation of targeted initiatives, including developing a strong safety culture, maintaining a balanced approach to the use of technology, and managing fatigue.

4.3. Population and Sampling

The population of the study involves active mariners who operate passenger ships, ferry vessels, terminal operation tugs, and supply offshore vessels. Purposive sampling approach was employed for hiring participants playing diverse roles (i.e., Masters, senior deck officers, senior engineer officers, Incident Investigators, Marine manager and crew members) for collecting richer, experience-derived information. Participants consisting of 50 maritime specialists were from different ship types and organizations.

4.3.1 Data Collection Tools

• Quantitative Component:

A structured online questionnaire consisting of 16 items was sent to seafarers using Google Forms. The questionnaire questions assessed factors including:

- Perceived levels of complacency
- Fatigue indicators
- Job satisfaction
- Organizational culture and leadership practices
- Experience with automation and monitoring systems

Likert-scale 5 were used in the survey to measure answers, allowing for statistical analysis of the correlations between variables.

• Qualitative Component:

Semi-structured interviews were conducted with some of the seafarers to capture detailed descriptions and individual life histories about complacency, fatigue, and safety behavior at sea. The qualitative approach served well to explore intricate, context-dependent phenomena that do not lend themselves easily to quantification in terms of numbers.

5- Data Analysis

- Descriptive statistics, correlation analysis, and ANOVA were implemented to evaluate the proposed hypotheses and identify statistically significant trends in quantitative data.
- Qualitative data were systematically categorized and thematically analyzed in accordance with Sutton & Austin's (2015) qualitative framework to discern recurrent patterns in seafarers' experiences and perspectives.

6- Literature review

Complacency, characterized by a state of satisfaction or a lack of vigilance, can have severe consequences for seafarers' behaviors and maritime safety. This literature review explores the negative impacts of complacency on seafarers' behaviors, with a focus on its implications for accidents, human error, and overall safety.

Karthik (2022) explored the consequences of complacency in maritime operations, identifying it as a critical form of human error that contributed to ship accidents. His study reviewed maritime incidents over the past century to assess their impact on safety and offered recommendations to maintain vigilance in routine, emergency, and critical operations.

Bielić & Zec (2005) examine complacency in port commercial operations, highlighting its role as a contributing factor to human error in ship accidents and port activities. Their research investigated the causes of complacency and its impact on decision-making in maritime and port operations.

Bielić (2008) examined complacency as a critical factor contributing to maritime accidents, analyzing its role in human error and its overall impact on maritime safety. His research highlighted how poor communication, weak cooperative relationships, and the influence of modern technology contributed to complacency, ultimately leading to inadequate decision-making and inefficient actions.

The interaction of fatigue with the self-satisfaction of seafarers is a very important factor in determining the procedures and outcomes in terms of maritime safety. Seafarers quite often feel fatigued a condition characterized by reduced alertness and degraded cognitive performance-because of the demanding work schedules they have to adhere to, including lengthy periods away from home and irregular sleep. Various research on maritime work has established, beyond doubt, the debilitating effects of fatigue on safety practices and decision-making. Such studies as that conducted by (Bloor et al., 2019) have outlined how fatigue contributes to attentional breakdowns, delays in response times, and increased chances of mistakes when on board. Complacency-a state characterized by feelings of self-satisfaction, reduced alertness-acts synergistically to increase the influence of fatigue. The problems caused by fatigue are further deteriorated by the tendency of seafarers to become heedless about the potential dangers and less responsive to stimulation. Multi-dimensional interventions should be designed for a decrease in the correlation between the self-satisfaction of seafarers and their fatigue level. Following the IMO Fatigue Recommendations for the implementation of efficient fatigue management techniques. This is an essential first step

Workload optimization, rest-hour regulations, and circadian rhythm problems should be covered in such programs.

For example, a fatigue monitoring system combined with intelligent algorithms provides real-time analysis of the crew members' status about their level of fatigue and enables corrective actions well in advance. Education and Training Programs: One may consider that the general public has been sensitized regarding the effects of fatigue and complacency. The crew members should be provided with the means to identify and mitigate those risks and enhance the on-board proactive safety culture. Furthermore, organizational policies ensure adequate rest periods, effective staff rotation strategies, and judicious use of technology in order to reduce the workload of those jobs causing fatigue, thus enhancing general safety. (Yuen, Li, Ma, & Wang, 2020).

The addressing of fatigue risk management in operational planning, frequent breaks, and good open reporting for fatigue-related matters ensure better maritime safety procedures.

Seafarer fatigue and complacency are intertwined in a complex, which is best approached through multi-faceted solutions involving crew education, technological advancement, legislative action, and regulatory commitment to the principles of safe maritime. (Chauvin, et al., 2013)

7- Organizational Culture and Leadership Factors

Safety is the primary focus of maritime operations due to the inherent risks involved in seafaring. The behaviour of seafarers is shaped and fostered by the organizational culture, which acts as a fundamental framework in this regard. It signals a commitment to safety procedures, constant training, and alertness in the identification and mitigation of potential risks. The culture of safety is inculcated into the very core of the organization's identity and permeates every aspect of maritime operations, rather than being a box-ticking exercise to satisfy regulatory requirements. Academics and researchers determine that safety culture is the most influential variable to achieve accident reduction and generally improve the whole safety performance within the shipping industry. References (Mansournia, et al., 2021). By embedding safety into an organization's culture, the people and assets become better protected, and the risk is reduced since it becomes a set of shared beliefs, values, and attitudes, not just a question of rules. A proactive attitude toward safety from top management reverberates throughout the organization, sending the clear message that safety is non-negotiable.

When leaders prioritize safety, it permeates the organizational fabric, empowering seafarers at all levels to prioritize safety in their decision-making and actions. The cultivation and nurturing of this safety-focused culture within maritime organizations relies heavily on leadership.

A commitment to safety is embodied by effective leadership through concrete actions, resource allocation, and communication strategies; through open communication, reporting mechanisms, and technology and training investments, leaders create an environment where safety becomes an

integral part of the organization's culture. The relationship between organizational culture and leadership is essentially mutually beneficial, highlighting the industry's shared commitment to safety.

In the organizational culture of maritime operations, communication plays a complex and crucial role in preventing complacency among seafarers. It goes beyond simple information sharing; good communication turns into a critical component that profoundly affects the safety, operational effectiveness, and general well-being of seafarers (Ajayi & Udeh, 2024). Building a strong safety culture necessitates a focused effort on fostering an atmosphere that values candid and open communication because complacency can have major repercussions in the maritime industry. Establishing an atmosphere where seafarers feel empowered and committed to reporting issues, near misses, or potential hazards without fear of reprisal requires establishing trust, maintaining confidentiality, and taking down any obstacles that might obstruct the free exchange of information (Ogedengbe et al., 2024). Leadership plays a central role in shaping this communicative culture. Leaders must do more than just recognize the importance of communication;

Open communication of ideas and opinions is encouraged between crew members and supervisors both in group sessions and one-on-one conversations. Employees may not always have their suggestions implemented, but they still have a voice.

8- Human factors that lead to complacency.

Seafarers' behaviours when on board at sea is inextricably linked with maritime safety and operations. Decision-making, communication, and teamwork among seafarers-their behavioural and psychological characteristics-affect all critical elements of maintaining the safety of the ship. Inherent stress, fatigue, fluctuations in workload, and complacency associated with marine work have a negative effect on the performance of individuals and their correctness in decisions. In emergency situations, the psychological readiness and flexibility of the crew determine how they will respond to the crisis, making human interaction even more important. Dominguez-Péry et al. (2021)

One of the most decisive factors is the repetitive and boring nature of the nautical tasks, especially during long voyages. Long ocean journeys, which are often characterized by dull work and low motivation may make workers more complacent and less vigilant. Dependence on the complex navigation system and automation is another reason. These make the operation more efficient. However, it inadvertently fosters overdependence, which reduces employee alertness and vigilance. (Fan & Yang, 2018)

The degree of complacency varies throughout various kinds of ships and marine activities for instance, long-distance bulk carriers and container ships may be especially affected by boredom at sea and the automation of certain tasks, which could raise the risk of complacency. (Fan & Yang, 2018; Bielić et al., 2020).

• The Psychological Changes

Maritime Labour Convention 2006 highlighted the mental health of seafarers. In fact, Article 4.3 of the MLC explained under Title 4 - Protection of Health, Medical Care and Welfare and Social Security Protection, stating the acknowledgment of the contribution of the maritime working environment to the mental health of seafarers.

MLC provides that seafarers are entitled to rights no less than those of all other workers with respect to care for their mental and emotional well-being, in addition to protection from physical harm. People who spend considerable time in what is often the small and sometimes lonely environment of a ship may also become complacent due to habituation: a condition whereby they feel accustomed to the routines and tend to become less sensitive to everything around them outside of their immediate task (Endsley, 1995; Bielić et al., 2020).

Complacency signs are described by a lack of alertness, less care towards safety procedures, and lowered risk.

Technology plays a crucial role in shaping seafarers' attitudes toward their work and responsibilities. While automation reduces physical strain and cognitive load—particularly in navigation and engine control—it also affects situational awareness. Automation-induced complacency, as described by Endsley (1995), occurs when excessive reliance on automated systems diminishes sailors' sense of responsibility and vigilance. Pazouki et al. (2018) explore human-automation interaction in maritime operations, shedding light on both its benefits and risks. While automation enhances efficiency and reduces workload, over-dependence on these systems can compromise decision-making and situational awareness, leading to potential errors. The maritime industry has embraced automation to improve safety and operational efficiency, but this shift presents a challenge: seafarers' ability to maintain focus and react swiftly may decline as automated systems take over critical tasks. To address this, the industry must emphasize training, risk awareness, and proactive strategies that empower seafarers to stay engaged in their roles. The key is balance—leveraging technological advancements while ensuring human expertise remains central to operations. As automation continues to evolve, fostering adaptability and resilience among seafarers will be essential (Balduzzi, Pasta, & Wilhoit, 2014).

9- Impact of Autonomous Surface Ships on Crew Behaviour and Decision-Making

Maritime Autonomous Surface Ships (MASS) is a relatively new and promising development in the maritime sector offering many potential benefits in terms of sustainability, efficiency and safety. MASS are unmanned vessels that operate without human intervention, thanks to advanced sensors, artificial intelligence, and independent navigation systems. The integration of MASS into the maritime industry is based on several drivers such as technological, regulatory, and industry initiatives. With MASS, safety can be increased because it reduces human error and enables the vessel to become more capable of handling itself. Advanced sensors and navigation systems can notice obstacles and, therefore, avoid them, navigate along complex maritime environments independently, and react against changes in weather conditions. All this may contribute to mitigating risks concerning accidents and collisions and, therefore, increasing general safety in the

maritime transport sector. (Islam, 2024). While the advent of (MASS) herald's significant changes for the maritime sector, it is also likely to introduce complacency and alter seafarers' behaviour and attitudes. Proper understanding of these dynamics is essential for the safe and efficient operation of automated vessels. The reaction among seafarers concerning the introduction of (MASS) ranges from scepticism and anxiety to curiosity. Some working on ships may initially fear that the automation will take away their jobs. Yet, some seafarer could be happy with this technology, believing it will make maritime operations safer and more efficient. These different feelings can affect how seafarers react to and adapt to the new technology. Issa, M., Ilinca, A., Ibrahim, H., & Rizk, P. (2022).

One possible effect of integrating MASS is that sailors may become complacent. This occurs when people don't pay as much attention or feel as urgent about something. With the use of this technology, individuals may become less attentive and may not make decisions independently. They might start to fully trust the automation, believing it will handle all aspects of the journey without their input. This reliance on the system can lead to reduced vigilance and, consequently, accidents. Choon, T. W. J. (2023).

10- The Key Factors Contributing to Complacency Questionnaire

A dedicated questionnaire was designed to gather insights from experienced professionals in the marine industry, including masters, senior officers, marine managers, and incident investigators, to explore this issue. The purpose of the questionnaire, the procedure for data gathering, and the data processing technique that were employed to obtain actionable insights into seafarers' complacency were discussed in this chapter. The survey was distributed via Google Forms, which provided a productive and intuitive way to connect with marine experts.

10.1 Data Collection and Processing

The survey was distributed via Google Forms, which provides a productive and intuitive way to connect with marine experts. The form contained 16 questions in all, divided into parts to address different aspects of complacency. Among the questions were the following:

1. Multiple Choice Questions: Collected quantitative data on respondents' experiences and opinions.
2. Important issues had binary answers, like Yes/No Questions.
3. Line-paragraph responses allowed for qualitative insights and encouraged extensive comments on events and mitigation techniques.

A total sample size of (50) Professionals spread across different profiles involved in the maritime industry had been mailed the questionnaire so as to get a response on the complacency issues from different angles. Response collection was allowed four weeks and generated an adequate sample size to result in informative data.

10.2 The Data Processing

Quantitative Analysis:

The multiple-choice and yes/no responses were processed using statistical methods, including frequency distributions and percentages. This helped to quantify respondents' views on the factors contributing to complacency and its impact on safety. For example, 34.7% of respondents cited routine and monotony as a primary contributor to complacency, while 66.7% of respondents reported that complacency levels vary across different types of vessels.

Qualitative Analysis:

Open-ended responses were thematically analyzed to extract deeper insights into real life incidents involving complacency. Common themes such as overconfidence, inadequate use of personal protective equipment (PPE), and the psychological impact of long working hours were highlighted. These narratives provided context to the statistical data, illustrating how complacency manifests in day-to-day maritime operations.

11- Results of Statically Analysis:

11.1 Factors Contributing to Complacency on Maritime Industry

Highlighting both the cognitive and operational factors, the results indicate that the job repetitiveness (34%) and overconfidence in skills and knowledge (32%) are the greatest contributors to complacency in the maritime industry. The other contributors are insufficient training (12%), multifaceted causes (12%), and fatigue due to long working hours (10%). The findings suggest that system-wide interventions, including more training, non-technical skills development, and organizational support, are needed to prevent overconfidence and create a safer, more productive work culture.

Table 1. The research sample respondent to what the factors are contributing to complacency on maritime industry (n= 50).

Factors	Frequency	%	Order
Routine and monotony of tasks	17	34%	1
Overconfidence in skills and experience	16	32%	2
Lack of adequate training	6	12%	3
All	6	12%	4
Fatigue and long working hours	5	10%	5

11.2 The Variations in Complacency Levels Among Seafarers on Different Types of Vessels (e.g., cargo, passenger, tanker)?

A majority of respondents (67%) assert that seafarers' complacency levels differ across different kinds of vessels, such as cargo, passenger, and tanker ships. This indicates that vessel type influences several aspects. This may result in complacency due to the unique operational

environments, responsibilities, and challenges associated with each vessel. Nevertheless, 33% of respondents failed to see such changes, indicating that complacency may stem from industry-wide issues rather than those particular to individual vessels. Successfully mitigating complacency may need both vessel-specific solutions and industry-wide modifications (Table 2).

Table 2. Complacency's levels on board different vessels according to the research sample (n = 50).

Effect level	Frequency	%
Yes	33	67%
No	17	33%

11.3 The Relation Between Complacency and Incidents

The data clearly shows that anchoring is a leading cause of maritime accidents, with 72% of respondents agreeing that anchoring is a leading cause of maritime accidents. Reported incidents include carelessness in handling equipment, disregard for safety protocols, and poor judgment under pressure and overconfidence. Accidents like lost anchors, collisions, fatigue errors, and neglect to use (PPE) indicate the extent to which poor organization and conduct compromise safety. The conclusions support that safety culture, accountability, and safety awareness need to be enhanced in an effort to reduce the risks involving the cruise ship population (Table 3).

Table 3. Complacency's effect on maritime accidents according to the research sample (n = 50).

Effect level	Frequency	%
Not at all	5	10%
To a small extent	9	18%
To moderate extent	23	47%
To great extent	13	25%

11.4 The Relation Between Fatigue and Complacency

Research has shown that there is a strong link between well-being and fatigue and that despite legal regulations, fatigue continues to be a major problem in the shipping industry. Findings by Rajapakse & Emad (2023) showed that there were many challenges, such as job insecurity, staff shortages, the absence of sedentary work, and increased stress due to technology. To address these issues, institutional-level changes were required. Effective methods to reduce fatigue and improve safe and healthy working conditions for seafarers included, among others, introducing more humane design options, reducing administrative tasks, increasing staff support, and providing adequate rest periods (Table 4).

Table 4. The relation between fatigue and complacency according to respondents' point of view (n = 50).

Relation	Frequency	%
Sometimes	23	46%
Often	10	20%
Always	6	12%
Rarely	9	18%
Never	2	4%

11.5 The Strategies Effectiveness in Mitigating the Impact of Fatigue-related Complacency.

The data highlights that [adequate rest periods and scheduling] are the most effective strategies in mitigating fatigue-related complacency, with the majority of respondents (53%) identifying this as the top solution. This underscores the importance of prioritizing rest and ensuring well-structured work schedules in the maritime industry. Fatigue management training (20%) and rotational shifts (14%) follow as additional impactful strategies, emphasizing the need for both educational and operational approaches to address fatigue. Lesser emphasis is placed on strategies like regular health checks (8%) and the use of technology to monitor fatigue (5%), which suggests they are perceived as supplementary rather than primary measures (Table 5).

Table 5. The research sample respondent to what the strategies which are most effective in mitigating the impact of fatigue-related complacency? (n= 50)

Factors	Frequency	%	Order
Adequate rest periods	26	53%	1
Fatigue management training	10	20%	2
Rotational shifts	7	14%	3
Regular health checks	4	8%	4

11.6 The Impact of Organizational Culture on Complacency

In the same context, a study by Shin & Shin (2023) examined the awareness and utilization of relevant technologies in shipping liners, which played a central role in maritime transport toward the 4th Industrial Revolution (4IR). A questionnaire survey conducted by 38 domestic and overseas shipping companies revealed that cloud server technology, Internet of Things(IOT), blockchain, and Big Data are forecasted as core technologies in the field. Container terminal, forwarder, and Information and Communication Technology (ICT) companies are perceived as potential collaborative partners. The firms involved were divided into four organizational culture

types: rational, developmental, hierarchical, and consensus, and four organizational strategy types: prospector, defender, analyzer, and reactor. Analysis of Variance (NOVA) test was used to compare the mean values of shipping liner firms across distinctive organizational culture types and strategies. Shipping liners with rational and developmental cultures were found to be more aware of the 4th IR compared to other firms, while the latter was observed to be the most active in utilizing 4th IR technologies (Table 6).

Table 6. The impact of organizational culture on complacency according to research respondents.

Effect level	Frequency	%
Very high	4	8%
High	13	26%
Moderate	24	48%
Low	6	12%

11.7 The Leadership Effectiveness in Reducing the Complacency

The data emphasizes that leadership plays a crucial role in reducing complacency within the maritime industry. Among the strategies assessed, regular safety drills are identified as the most effective, with 22% of respondents ranking them highest.

This highlights the importance of consistent preparedness and fostering a safety-conscious culture. 88 Other strategies, including fatigue management training, rotational shifts, and regular health checks (each at 20%), share significant recognition, indicating a need for comprehensive approaches addressing both physical and operational aspects. Meanwhile, the use of technology to monitor fatigue (18%) is seen as a valuable but slightly less prioritized method. Overall, the findings suggest that leadership should adopt a multi-faceted strategy, integrating both proactive safety measures and health management practices, to effectively mitigate complacency risks (Table 7).

Table 7. The research sample respondent to The leadership may be effective to reduce the complacency (n= 50).

Factors	Frequency	%	Order
Regular safety drills	11	22%	1
Fatigue management training	10	20%	2
Rotational shifts	10	20%	3
Regular health checks	10	20%	4
Monitor fatigue	9	18%	5

11.8 The Most Effective Training Programs.

In order to effectively incorporate complacency-reduction training into the marine curriculum, a synthesis of academic, psychological, and practical approaches is necessary. It is advised that these programs be incorporated into the STCW requirements, essential marine training, and continuous professional development. The emphasis is on workshops in real-world settings, simulation-based education, periodic remedial courses, and training in human factors, emotional intelligence, and cultural sensitivity. Additionally, the development of a training culture that prioritizes safety and is proactive necessitates the collaboration of corporate management and crew members through legislative support and awareness campaigns (Table 8).

Table 8. The research sample respondent to The Most Effective Training Programs (n= 50).

Factors	Frequency	%	Order
Simulation-Based Training	14	28.6%	1
Safety Awareness Campaigns	13	26.5%	2
Peer-to-Peer Mentoring	9	18.4%	3
Regular Safety Workshops	8	16.3%	4
Online Courses and E-Learning	6	10.2%	5

11.9 The Impact of Technology on Reducing Complacency.

The data reveals that technology is perceived as a significant tool for reducing complacency in the maritime industry. A combined 68% of respondents believe it has an impact either to a moderate extent (46%) or to a great extent (22%). However, a smaller portion sees its effect as limited, with 18% attributing it to a small extent and 14% believing it has no impact. This highlights technology's potential but underscores the need for its strategic implementation to maximize effectiveness (Table 9).

Table 9. The impact of Technology on Reducing Complacency according to research respondents.

Effect level	Frequency	%
To a Moderate Extent	23	46%
To a Great Extent	11	22%
To a Small Extent	9	18 %
Not at All	7	14

12- Conclusion:

Complacency is not only a passive attitude; it is an active risk factor that arises from a number of interrelated factors that increase the likelihood of mistakes and mishaps.

- Routine and boredom were the most cited causes, with 34% of the respondents citing these as the root causes. Due to the repetitiveness of the nautical tasks they may lead to a drop in alertness and vigilance during which even small mistakes can get blown into major accidents.
- The second most important theme was that of loss of concentration, generally fostered by overconfidence. 32% comments were related to overconfidence in their own capability and expertise: this again underscores how an experienced can make the mistake of underestimating the hazards or deviate from a work practice; 50% said that it was occasionally due to fatigue brought in by them into operations.
- Physical and mental fatigue brought about by the rigors in marine scheduling, long hours of work, and little sleep detract from the competence of an individual to concentrate and perform tasks at hand.
- It identified organizational culture and leadership as key in forming attitudes and behaviours associated with complacency. Generally stated was the fact that a good safety culture, characterized by open communications, frequent training, and capable leadership, will ensure the best countermeasure against complacency.
- The poor organizational practices were believed to contribute to the worsening of the problem, including poor staffing, poor supervision, and poor application of safety policy. 56% of the respondents cited culture as necessary to fight complacency, which suggested the necessity for involvement of systemic solutions as opposed to simple individual acts.
- The clear linkage of complacency to accidents in the maritime field was shown to have 48% of all respondents citing high-impact factor accidents. It is also indicated that these minor, careless mistakes range from negligible near-misses up to disasters.

13- Recommendations:

- Identification and Treatment of the Most Relevant Factors Contributing to Complacency.
- Provide fatigue management training when necessary. Sequencing of work Rest - Adequate Health checks to maintain physiological and psychosocial fitness. Monitoring fatigue through the vessel on board device installed on board.
- By pro- active safety culture, reporting and learning from incidents leadership training with safety focus and accountability. More frequent Drills and workshop pay attention to Good habits.
- Simulation-based training, inclusion of realistic scenarios in the marine courses, refresher lectures every month regarding the standards for safety and mitigation of complacency, emotional intelligence, and cultural diversity training within your professional development.
- Arrange safety work involvement by ship owners, trade associations and marine administrations. Also, improve consultation from top level management down to the crews with the goal of securing effective compliance and implementation. Increase mutual

recognition by all players involved in marine activity of shared concern for improving the structural areas.

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- [The Complacency Among Seafarers - Google Forms](#)

Assessing the Impact of Automating the Operational Processes at Khalifa Port using SWOT Analysis

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المستخلص:

يمثل توجه ميناء خليفة نحو الأتمتة مبادرة استراتيجية تسهم في تعزيز قدرته التنافسية، وتحسين كفاءة عملياته التشغيلية وأنظمة تشغيل المحطة في محطة الحاويات، ودعم الترابط مع التجارة العالمية. ومع استمرار الميناء في التطور وتبني تقنيات جديدة، فإنه لا يعزز مكانته كقائد إقليمي في الصناعة البحرية فحسب، بل يساهم أيضاً في استدامة ونمو الاقتصاد الإماراتي. من خلال معالجة نقاط الضعف مثل فجوات القوى العاملة، واستثمار الفرص كالشراكات الذكية، فإن ميناء خليفة مؤهل للحفاظ على موقعه كمركز عالمي للتجارة الفعالة والمستدامة والمستعدة للمستقبل.

يهدف هذا البحث إلى تقييم أثر الأتمتة في تحسين الكفاءة والتنافسية بميناء خليفة، مع تحديد التحديات أو القيود التي قد تعيق تحقيق هذه الأهداف بشكل كامل. يتبع البحث منهجاً وصفيًا باستخدام تحليل (SWOT) وقد خلص إلى أن ضمان استمرارية تنافسية الميناء واستعداده المستقبلي يتطلب تبني مجموعة من التوصيات الاستراتيجية، أبرزها الاستثمار في تقنيات مرنة ومقاومة للمخاطر، من خلال اعتماد أنظمة أتمتة قابلة للترقية والتطوير تستجيب للتغيرات المستقبلية، مع بناء بروتوكولات للتكرار مثل أنظمة الطاقة الاحتياطية وخيارات التجاوز اليدوي لتقليل مخاطر التوقف. من بين التحديات الرئيسية: التهديدات السيبرانية، والتقدم التكنولوجي الذي قد يؤثر على الاستقرار التشغيلي ويتطلب تحديثات مكلفة. كما تمثل المنافسة الإقليمية الشديدة والتقلبات الاقتصادية العالمية مخاطر على عوائد الاستثمار في الأتمتة. بالإضافة إلى ذلك، قد يؤدي الرفض الاجتماعي لفقدان الوظائف إلى فرض قيود تنظيمية.

الكلمات المفتاحية: أتمتة العمليات التشغيلية، ميناء خليفة، تحليل SWOT ، الإمارات.

Abstract

Khalifa Port's journey towards automation is a strategic initiative that enhances its competitiveness, improves operational efficiency and its terminal operating systems in container terminal; supports global trade connectivity. As the port continues to evolve and adopt new technologies, it will not only solidify its position as a regional leader in the maritime industry but also contribute to the sustainability and growth of the UAE's economy. By addressing weaknesses such as workforce gaps and capitalizing on opportunities like smart partnerships, Khalifa Port is poised to maintain its leadership role as a global hub for efficient, sustainable, and future-ready trade.

This research aims to evaluate the impact of automation on improving the efficiency and competitiveness of Khalifa Port, while also identifying any challenges or limitations that may prevent the port from fully achieving these objectives. This research follows a Descriptive approach using SWOT analysis. The research concluded that to ensure Khalifa Port's continued competitiveness and future readiness, several strategic recommendations should be considered. First, investing in resilient technology is crucial. This involves prioritizing modular, upgradable automation systems that can adapt to future innovations, along with building redundancy protocols, such as backup power and manual override options, to mitigate risks of downtime. Key challenges and limitations include cybersecurity threats and technological obsolescence that may hinder operational stability and require costly updates. Intense regional competition and global economic shifts pose risks to return on automation investments. Additionally, social resistance to job displacement could lead to regulatory constraints.

Keywords: Automating the Operational Processes, Khalifa Port, SWOT, Emirates.

1- Introduction

Khalifa Port is a state-of-the-art deep-water port in the United Arab Emirates, strategically located between Abu Dhabi and Dubai. As one of the most advanced and automated ports in the region, it plays a crucial role in connecting the UAE to global trade routes. Khalifa Port serves as a major gateway for international shipping, offering cutting-edge infrastructure, including fully automated container terminals and advanced logistics services, which enhance operational efficiency and competitiveness. With its strategic position and robust capabilities, the port is a critical hub for the region's maritime and trade activities, contributing significantly to the UAE's economic growth and global trade connectivity.

The maritime industry is an essential pillar of the modern global economy (Zaychenko et al., 2021). Seaports and maritime carriers form the backbone of the global supply chain, playing a pivotal role in ensuring the smooth and timely transportation of goods worldwide. For instance, the layout of a port plays a pivotal role in its efficiency, as it impacts the speed with which cargo is loaded and unloaded from ships and moved through the port. Ports that achieve high technical efficiency can handle larger cargo volumes and provide faster ship turnaround times, leading to significant cost savings for shippers and carriers. On the other hand, ports that lack technical efficiency often face congestion, delays, and higher operating costs, which diminish their competitiveness in the global trade market (Elgazzar, and Ismail 2021).

Automation at Khalifa Port will enhance operational efficiency by speeding up cargo handling, reducing human error, and optimizing container management. Automated systems will also lower operational costs by reducing labor reliance and improving energy efficiency. Faster turnaround times and increased capacity will make Khalifa Port more competitive, attracting more global shipping lines. Additionally, automation will improve safety by minimizing risks and enabling predictive maintenance, while also contributing to sustainability by reducing emissions and optimizing energy use. In this context, (Hafez, and Elbayoumi, 2024) stated that the level of automation significantly affects inefficiencies in container ports.

Khalifa Port is one of the largest and most advanced ports in the Gulf region, boasting a container handling capacity of 7.8 million TEUs per year, 25 million square feet of general cargo capacity, and the ability to handle 15,000 vehicles via RoRo operations. The port features a quay wall stretching 10,795 meters, 36 berths, and 33 ship-to-shore cranes, along with a draft depth of 18.5 meters, enabling it to accommodate ultra-large vessels across various cargo types. These capabilities are supported by state-of-the-art infrastructure and integrated on-site warehousing facilities, positioning Khalifa Port as a versatile, multi-purpose hub essential to the UAE's supply chain and regional logistics leadership (Khalifa Port, 2025. Accessed 1-5-2025).

Khalifa Port holds a strategic position in the Gulf region due to its advanced infrastructure, deep-water capabilities, and integration with industrial zones such as KIZAD. However, when compared to global benchmark ports like Rotterdam, Singapore, and Jebel Ali, its level of automation, digital maturity, and innovation-driven performance still shows room for growth. For example, ports like Singapore lead in AI-powered logistics optimization and fully integrated port community systems, while Rotterdam excels in real-time data sharing, predictive maintenance, and environmental sustainability through its digital twin model. Jebel Ali, in the same regional ecosystem, benefits from early-stage automation investments and extensive hinterland connectivity. In contrast, Khalifa Port has made significant strides with automation and smart systems, but its performance metrics—such as vessel turnaround time, crane productivity (TEUs per hour), and integration with customs and inland transport—are not yet consistently on par with these leaders. To strengthen its global competitive position, Khalifa Port should focus on expanding AI and IoT integration, enhancing end-to-end visibility across supply chain operations, investing in predictive analytics for dynamic scheduling, and accelerating green logistics initiatives. Additionally, further collaboration with tech firms and regional logistics hubs could support the port's evolution toward becoming a fully intelligent and sustainable maritime gateway.

2- Literature Review

The studies collectively underline the transformative role of digitalization in the maritime transport sector, highlighting how modern technologies are reshaping port operations and enhancing efficiency, competitiveness, and sustainability. As digitalization impacts all aspects of maritime logistics, it plays a central role in improving ports' integration within global digital networks and information chains, which is crucial for their competitive edge (Schröder et al., 2019; de la Peña and Bermúdez, 2020). Heilig et al. (2017a) and (2017b) argued that digitalization is driving the maritime industry beyond traditional boundaries, offering significant opportunities to improve productivity, efficiency, and sustainability in port logistics. The digital transformation of container terminals, for instance, aims to integrate modern technologies, enhancing collaboration, optimizing coordination, and improving management planning. These developments are particularly crucial for ports like Alexandria, where the adoption of systems like the Advanced Cargo Information (ACI) system has been found to streamline cargo flow, reduce operational costs, and mitigate congestion.

At the same time, Rajabi et al. (2018) emphasized the growing importance of the Internet of Things (IoT) in advancing port operations, defining "smart ports" as those integrating technologies such as IoT, RFID, big data management, and analytics. These technologies enable real-time decision-making, improve operational efficiency, and contribute to environmental sustainability by minimizing the ecological footprint of port operations. This technological shift supports Jović et al. (2019), who elaborate on how smart ports integrate various advanced technologies to optimize resource allocation, interconnect different functional units, and foster intelligent and secure port development.

The adoption of emerging technologies, as Mahwish (2019) noted, is progressing in major ports like Rotterdam, Singapore, and Hamburg, where digital technologies such as AI, cloud computing, and IoT are transforming container terminal operations. These advancements not only optimize port processes but also require significant investments in infrastructure and equipment. While these technologies enhance the competitiveness of major ports, they also pose challenges for smaller ports, which may not have the resources to implement such sophisticated systems. This aligned with Yau et al. (2020), who highlighted that the introduction of ICT solutions in ports demands a skilled workforce and contributes to the socio-economic development of the surrounding communities.

A detailed comparison between the studies revealed that Aifan and Al-Bawab (2024) have replicated the entire statistical section from Qardash et al. (2022). This replication includes identical details regarding the research population and sample, the number of valid and analyzable questionnaires, and the corresponding percentages. Furthermore, the commentary and interpretation of the statistical results were found to be nearly identical in phrasing and structure. Despite being published two years later, the 2024 study does not appear to provide any new statistical contribution beyond what was already presented in the 2022 study.

In line with these findings, Karas (2020) further explored the digital transformation in foreign trade management, particularly in supply chain operations. The study emphasized the importance of seamless communication among stakeholders, including shipping companies, customs authorities, and freight agencies, to maximize efficiency. This interconnection, supported by comprehensive ICT infrastructure, plays a critical role in streamlining the supply chain, reducing delays, and minimizing costs. Similarly, Brunila et al. (2021) and (Braidotti et al., 2022) highlighted the importance of integrating digital technologies to improve ports' competitiveness, underscoring that successful digital upgrades require advanced technological management to ensure smooth system interactions.

However, the adoption of digital technologies is not without challenges, as indicated by Knatz et al. (2022), who discussed the slow pace of automation adoption in container terminals globally. Despite the advantage's automation brings, including improved operational efficiency and reduced processing times, only a small percentage of global terminals are fully automated. This study stresses that not all terminals are suitable candidates for automation, and the decision to implement such technologies must consider factors such as cargo volume and the terminal's specific needs.

A recent study highlighted that digital transformation and automation have become fundamental components in enhancing port efficiency. The adoption of advanced technologies—such as automated loading and unloading systems, digital cargo documentation, and real-time tracking—has significantly improved operational performance. The study emphasized that digitalization enables ports to transition from rigid, manual procedures to more agile and responsive systems that adapt to changing market demands. It further pointed out that competitiveness among ports now hinges heavily on their digital readiness, as shipping companies can easily shift to ports offering more efficient and transparent services. This compels ports to adopt advanced digital technologies to maintain their strategic position in global trade (Lagdami et al., 2024).

Another study explored future trends in port digitization, arguing that digital transformation not only boosts operational efficiency but also acts as a catalyst for innovation and seamless integration across the maritime supply chain. It underscored the importance of technologies such as the Internet of Things (IoT), smart forecasting tools, and environmental monitoring systems in optimizing performance and reducing long-term operational costs (Heikkilä et al., 2022). The study stressed the need to balance economic and environmental goals by embedding sustainability principles into smart port development strategies. Such an approach, the study concluded, ensures long-term growth and resilience in port operations (Subasinghe, 2024).

Knatz et al., (2024) highlighted the strategic significance of automation in container terminals by examining the factors that influence automation decisions and the extent to which the anticipated benefits are realized in practice. Automation is positioned as a transformative investment, promising improvements in terminal efficiency, reliability, and long-term competitiveness. The main objective of the study was to identify and analyze the key drivers behind automation decisions and evaluate how closely the expected benefits matched actual outcomes once terminals became operational. Methodologically, the research adopted an empirical, survey-based approach, gathering data from senior executives of companies operating fully or semi-automated container terminals. Statistical tools—including descriptive analysis, Pearson correlations, ANOVA, and Kruskal-Wallis tests—were used to interpret the results. The findings revealed that while many anticipated benefits of automation were indeed realized, in several cases expectations exceeded actual outcomes, or vice versa. Furthermore, stepwise regression analysis uncovered causal relationships between automation drivers and realized benefits, in connection with terminal characteristics such as technical infrastructure, organizational structure, and market context. While explicit recommendations were not stated, the study implicitly suggests the need for more realistic forecasting, context-aware planning, and ongoing evaluation when pursuing automation projects in the port sector.

A comprehensive analytical study examined the impact of artificial intelligence (AI) on port performance across various regions including Europe, Asia, and North America. The findings revealed that AI applications—such as predictive maintenance, autonomous scheduling, smart vehicles, and big data analytics—have led to substantial improvements in productivity and the reduction of human error. Ports like Singapore and Rotterdam were cited as global benchmarks,

having significantly advanced their operational agility through strategic investments in AI. The study concluded that adopting AI not only increases adaptability to market fluctuations but also supports fast, data-driven decision-making, positioning ports to meet future challenges more effectively (Osundiran & Makgopa, 2025)

Given the rapid global expansion of port automation technologies, future studies on Khalifa Port should move beyond general assessments of automation impact and instead conduct detailed analyses of key operational performance indicators, such as vessel turnaround times, container handling rates per hour, and cost-efficiency before and after automation implementation. Comparative studies are also essential—particularly with regional competitors such as Jebel Ali Port and King Abdullah Port—to assess Khalifa Port’s relative positioning within the Gulf and global maritime landscape.

Additionally, future research should explore human and institutional adaptation to digital transformation by analyzing workforce impacts, levels of acceptance, and retraining or reskilling strategies adopted in response to automation. A critical area of inquiry is the economic feasibility of automation, particularly in terms of long-term return on investment, recurring upgrade costs, and the challenges of technological obsolescence. Applied research is also recommended to investigate the technical integration of port automation systems with customs operations, inland transport networks, and smart logistics platforms, since the effectiveness of automation depends not only on internal efficiencies but also on the port’s ability to operate as part of a digitally integrated ecosystem. Finally, future studies could assess the digital maturity of Khalifa Port using structured frameworks such as Digital Port Maturity Models, which help identify gaps and prioritize phased improvements in alignment with global best practices (Knatz et al., 2024).

Automation in container terminals is a growing trend in the global port sector, primarily driven by the pursuit of enhanced efficiency, reduced operational costs, mitigation of labor shortages, and increased overall productivity (De Alwis, and Nam, 2024). However, the study acknowledges a critical gap between expectation and reality, as there is currently no conclusive evidence that automated terminals consistently outperform conventional terminals in key performance metrics such as handling productivity, cycle times, or vessel berthing durations. The objective of the article was to examine actual productivity rates in automated terminals, explore the factors influencing these outcomes, and assess the potential of future technological advancements to resolve current inefficiencies. The research utilized multiple data sources and analytical approaches to investigate the real-world performance of automated port operations. The findings suggest that, despite the cost-saving potential of automation, it does not necessarily lead to productivity improvements, and in some cases, automated terminals demonstrate lower performance than their conventional counterparts. Furthermore, semi-automated terminals remain the preferred model due to superior handling times. Nevertheless, the study concludes with cautious optimism, forecasting that future technological innovations may eventually resolve these limitations and lead to a paradigm shift in terminal automation effectiveness (Majoral et al., 2024)

The study by Yu et al. (2022) highlights the growing importance of automation in container terminal yard operations, emphasizing its role in enhancing efficiency, minimizing labor dependency, and improving safety in increasingly complex and high-volume port environments. Automation enables terminals to operate continuously with reduced human error, supporting the rising demand from mega-vessels and streamlining labor-intensive processes. The objective of the study was to systematically review and synthesize the existing body of literature on yard operations in Automated Container Terminals (ACTs), identify the key research developments, and uncover gaps that require further exploration. To achieve this, the authors conducted a structured literature review, extracting 628 articles from the Web of Science database and narrowing them down to 75 highly relevant papers. These were analyzed using keyword mapping and cluster analysis tools (VOSviewer) to identify dominant research themes and categorize contributions. The findings revealed that, despite notable advancements, the current research landscape remains fragmented, with major challenges including inefficient yard layouts, high re-marshalling complexity, and weak integration between automated systems and storage logistics. The study concludes with a strong recommendation to pursue integrated scheduling models that align equipment operations with optimal yard space utilization. Furthermore, the authors call for more empirical studies and real-world validations to ensure that academic research aligns closely with the operational realities of container terminals.

Al-shabi and Elbayoumi (2024) explored the impact of automation at the Aden Container Terminal, finding that the introduction of automation and modern technology significantly boosted its competitiveness by reducing inefficiencies and enhancing inter-departmental coordination. This positive impact is echoed by Abdelkarim et al. (2024), who assess the effectiveness of the ACI system at Alexandria Port. Using SWOT analysis, their study identifies the weaknesses and threats in the current system, offering insights into how digital transformation can enhance port performance by improving data management and document registration processes.

The research gap addressed in this study lies in the lack of previous research that directly assesses the impact of automating operational processes at Khalifa Port using SWOT analysis. To date, no academic work has integrated the concept of automation with strategic analysis in the context of UAE ports. Therefore, the current study represents a valuable scientific contribution, as it aims to fill this gap by employing SWOT analysis as a methodological tool to evaluate the effects of automation on operational efficiency, identifying strengths, weaknesses, opportunities, and threats within the port environment. The findings are expected to provide actionable insights to support decision-makers in the maritime and port sectors.

3- Port Automation

Smart is sometimes used as a euphemism for too-automated systems. Additionally, it describes the devices' monitoring and control mechanisms. Automation is the fusion of computer software, hardware, and mechanical components. Increasing the port's level of automation helps partners communicate more easily, cuts down on wasteful labor and idle time, provides speed, reliability, fluidity, and traceability, and boosts the technical efficiency of the port (Yang et al., 2018).

The smart port must have automated processes and equipment. This equipment must be obtained to successfully set up an automatic port (Douaioui et al., 2018)

3.1 Smart ships

To enhance system monitoring and control, smart ports are furnished with a satellite system, numerous sensors, and monitoring tools. The wait time for vessels at the port is reduced because of the smart port. The partnership between the port and the ship makes the port more intelligent because of the ship's significant marketing influence (Aslam et al., 2020).

3.2 Smart container or connected container

Many sensors built inside the smart container can be utilized to collect data on shock, pressure, and geolocation. It enables damage reporting by sending directly and remotely acquired data to the information system. Along the journey, the smart container delivers constant feedback, enabling the pilot and giving a global perspective of the fleet (Kupriyanovsky et al., 2018).

3.3 Automated operations

Operations that involve moving, storing, and managing containers inside the terminal are automated. Automation of transportation entails the use of transport platforms with electronic guidance in place of conventional trucks. Then, the storage activities involve the employment of rail cranes without an operator; as a result, an automated control system manages the storage and extraction of containers. Finally, automated dock cranes can quickly load and unload ships. The internal operations of the port terminal have been automated, which lowers energy usage while reducing waiting times for trucks and ships (Yen et al., 2023).

4- Research Problem:

As global trade grows, ports are becoming increasingly vital in ensuring the smooth flow of goods between regions. Khalifa Port, as a major maritime center, faces the challenge of boosting its operational efficiency and staying competitive in the global market. Although it boasts a prime location and cutting-edge infrastructure, the port must continue to innovate to maintain its competitive advantage. There are three main questions this research answer as follows:

- What are the key components of a smart and resilient automation infrastructure, and how do they contribute to ensuring operational continuity and minimizing disruptions at Khalifa Port?
- How can developing human capital through continuous training in technologies such as AI, IoT, and robotics enhance operational efficiency and preserve institutional knowledge in an automated environment?
- What are the major cybersecurity threats facing automated port systems, and how can effective security strategies be implemented to protect data and digital infrastructure?

5- Research Aim:

This research seeks to evaluate how automating operational processes can enhance the efficiency and competitiveness of Khalifa Port. The study focuses on the specific effects of automation on port operations, pinpoint potential challenges in adopting these technologies, and suggest strategies to address these issues.

6- Research Importance:

6.1 Scientific Significance:

The scientific significance of this study lies in its contribution to filling a clear gap in the academic literature, as no prior research has directly assessed the impact of automating operational processes at Khalifa Port using SWOT analysis. This study represents a novel contribution by integrating concepts of automation and digital transformation with strategic analytical tools, a combination rarely addressed in port-related research. Moreover, the analytical framework employed in this research can serve as a reference model for future studies in other local and regional ports.

6.2 Practical Significance:

The practical significance of the study is reflected in its ability to provide real, data-driven insights that support decision-makers at Khalifa Port in understanding the operational and strategic implications of automation. By identifying strengths, weaknesses, opportunities, and threats, the study helps enhance operational efficiency, inform evidence-based planning, and improve the port's competitive position regionally and globally. As such, the findings offer a practical tool for guiding future development and digital infrastructure investments in the port sector.

7- Research Methodology:

This research follows a Descriptive approach using SWOT analysis. The research assesses the port's strengths, weaknesses, opportunities, and threats in the context of automation, offering valuable insights into how the port can optimize its performance. Ultimately, the goal is to provide a clear roadmap for improving the port's operations and competitiveness in the rapidly evolving maritime industry.

The research adopted seven proposed questions to provide a thorough understanding of the impact and challenges of automation at Khalifa Port. In addition, defining the impact of automation on the efficiency and competitiveness of Khalifa Port. These questions are:

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?

In this study, SWOT analysis was employed as a strategic evaluation tool to assess the anticipated impact of automating operational processes at Khalifa Port. The analysis focused on identifying internal strengths and weaknesses, as well as external opportunities and threats associated with the port's transition toward automation. It was not used to compare pre- and post-automation performance or different automation strategies; rather, it was applied proactively to anticipate potential outcomes, evaluate risks, and understand the port's strategic positioning amid emerging technologies and regional competition. Importantly, this analysis was informed by direct, in-person interviews with key decision-makers at the port, adding a practical dimension to the findings and reflecting real-world executive and operational perspectives.

8- SWOT ANALYSIS:

1.1 Strengths:

8.1.1 Advanced Automation Infrastructure

- Khalifa Port employs cutting-edge technologies such as automated stacking cranes (ASCs), AI-driven terminal operating systems (TOS), and IoT-enabled sensors for real-time monitoring. These systems enable seamless coordination between landside and seaside operations, reducing idle time and optimizing cargo flow.
- AI algorithms predict container placement, minimizing rehandling and speeding up loading/unloading processes.
- 24/7 operational capacity ensures continuous productivity, even during peak periods or labor shortages.

8.1.2 Cost Efficiency and Profitability

- Automation reduces reliance on manual labor, lowering long-term labor costs and minimizing human error.
- Energy-efficient systems (e.g., electric cranes, solar-powered equipment) cut energy expenses and align with sustainability goals.
- Higher throughput and faster turnaround times increase revenue generation while maintaining competitive pricing for clients.

8.1.3 Global Competitiveness

- Khalifa Port ranks among the fastest ports in the region for vessel turnaround times, attracting major shipping alliances like 2M Alliance and Ocean Alliance.
- Integration with the UAE's National Rail Network and Abu Dhabi's Industrial Hub (KIZAD) enhances multimodal connectivity, positioning the port as a gateway for global trade.

8.1.4 Enhanced Service Quality

- Digital platforms provide clients with real-time tracking of shipments, improving transparency and trust.
- Automated systems ensure consistent service delivery, reducing delays and boosting customer satisfaction.

8.2 Weaknesses:

8.2.1 High Capital and Operational Costs

- Initial investments in automation infrastructure (e.g., ASCs, IoT networks) are substantial, requiring long payback periods.
- Maintenance of sophisticated systems demands specialized technicians, increasing operational expenses.

8.2.2 Integration Challenges

- Legacy systems in partner logistics networks may not align with Khalifa Port's automated workflows, causing delays in documentation or cargo transfers.
- Partial automation (e.g., manual customs clearance) creates bottlenecks, limiting end-to-end efficiency gains.

8.2.3 Workforce Adaptation

- Resistance from employees due to fear of job displacement or inadequate training slows adoption.
- A skills gap persists in managing AI and IoT systems, requiring costly external expertise.

8.2.4 Over-Reliance in Technology

- System failures or cyberattacks could halt operations, exposing vulnerabilities to fully automated processes.
- Limited flexibility to handle oversized or non-standard cargo that requires manual intervention.

8.3 Opportunities:

8.3.1 Adoption of Emerging Technologies

- Blockchain could automate and secure documentation processes (e.g., bills of lading, customs clearance), reducing administrative delays.
- Autonomous trucks and drones could enhance last-mile connectivity between the port and inland logistics hubs.
- Predictive analytics powered by machine learning could optimize inventory management and demand forecasting.

8.3.2 Regional and Global Partnerships

- Collaborate with tech giants (e.g., IBM, Siemens) to develop smart port ecosystems integrating 5G, AI, and edge computing.
- Partner with regional ports to create automated trade corridors, streamlining cross-border logistics.

8.3.3 Sustainability Leadership

- Leverage automation to achieve net-zero emissions through renewable energy integration and electrified equipment.
- Market eco-friendly practices to attract ESG-focused clients and comply with global climate regulations.

8.3.4 Economic Diversification

- Expand automation to support emerging sectors like e-commerce logistics and cold chain storage, tapping into UAE's vision for a knowledge-based economy.

8.4 Threats:

8.4.1 Cybersecurity Vulnerabilities

- Automated systems are prime targets for ransomware or data breaches, risking operational shutdowns and reputational damage.

8.4.2 Technological Obsolescence

- Rapid advancements in AI and robotics could outpace Khalifa Port's current infrastructure, necessitating frequent and costly upgrades.

8.4.3 Intense Regional Competition

- Rivals like Jebel Ali Port (Dubai) and King Abdullah Port (Saudi Arabia) are investing heavily in automation, threatening Khalifa Port's market share.
- Global hubs like Rotterdam and Singapore set high benchmarks for innovation, raising customer expectations.

8.4.4 Economic and Geopolitical Risks

- Global trade slowdowns (e.g., post-pandemic shifts, geopolitical tensions) could reduce cargo volumes, impacting ROI on automation investments.
- Regulatory changes (e.g., stricter emissions standards) may require unplanned upgrades.

8.4.5 Social Resistance

- Public backlash over job losses due to automation could lead to stricter labor laws or unionization efforts.

9- CYBERSECURITY VULNERABILITIES IN AUTOMATED PORT SYSTEMS

As automation becomes increasingly integral to port operations, the associated cybersecurity risks grow in both complexity and severity. Automated systems rely heavily on interconnected networks, real-time data flows, and control systems that, if compromised, can severely disrupt the operational integrity of a port. These systems are attractive targets for malicious actors due to the critical role ports play in global trade and logistics.

1. Ransomware Attacks: Ports are vulnerable to ransomware types of malwares that encrypts system data and demands payment for its release. In automated environments, such attacks can lock operators out of critical infrastructure such as terminal operating systems, cranes, and cargo tracking platforms. The 2017 NotPetya attack, which crippled Maersk's global operations for days, stands as a stark reminder of how ransomware can paralyze supply chains and cause massive financial and reputational damage.

2. Data Breaches: Automated ports handle vast amounts of sensitive data, including cargo manifests, trade documents, and customer records. Breaches can expose this information, leading to legal liabilities, loss of client trust, and potential compliance violations under

international data protection regulations (e.g., GDPR). In some cases, data theft may also provide attackers with insights into system vulnerabilities for future sabotage.

- 3. System Manipulation and Operational Sabotage:** Cyber attackers may infiltrate control systems such as Supervisory Control and Data Acquisition (SCADA) or Industrial Control Systems (ICS) to manipulate machinery or disruption processes. This can result in physical damage to port equipment, unsafe working conditions, and significant downtime. For example, altering crane algorithms or tampering with automated gate entries could halt cargo flow entirely.
- 4. Supply Chain Exploitation:** Ports are part of a broader ecosystem involving logistics providers, customs authorities, and shipping lines. A cyberattack targeting one node in the chain can propagate through connected systems. This interdependence increases the attack surface and highlights the importance of holistic cybersecurity practices across all stakeholders.

10- CONCLUSION

To ensure that automation continues to drive efficiency and competitiveness at Khalifa Port, a set of targeted recommendations is proposed, grounded in the findings of this study.

- 1. Invest in Adaptive and Resilient Automation Infrastructure:** Khalifa Port should prioritize modular and scalable automation technologies capable of evolving with future innovations. This includes integrating fail-safe mechanisms such as manual overrides, backup power systems, and redundancy protocols to minimize downtime and operational disruptions. Such preparedness will ensure operational continuity and flexibility in the face of technological or environmental uncertainties.
- 2. Strengthening Human Capital for a Technology-Driven Environment:** Addressing workforce limitations is essential to the success of automation. The port should develop continuous training programs centered on emerging technologies like AI, IoT, and robotics. These initiatives will not only close the digital skills gap but also enable the redeployment of displaced workers into high-value roles—such as data analytics, remote systems management, and customer experience optimization—thus preserving institutional knowledge and enhancing service quality.
- 3. Enhance Cybersecurity to Protect Automated Systems:** Given the increased exposure to cyber threats associated with automation, the port must implement robust cybersecurity strategies. Collaborations with leading cybersecurity firms to deploy advanced firewalls, encrypted data networks, and real-time intrusion detection systems will be essential to safeguard sensitive operations and ensure trust among global trade partners.
- 4. Leverage Sustainability as a Competitive Advantage:** Automation offers opportunities to improve environmental performance. Khalifa Port should build its green logistics identity by pursuing internationally recognized certifications (e.g., ISO 14001), transitioning to electrified equipment, and forming partnerships with eco-conscious shipping lines. These actions will not only align with global ESG standards but also enhance the port's appeal to environmentally responsible stakeholders.

5. Aligning with National Strategies through Strategic Partnerships: Long-term success requires collaboration beyond port boundaries. Khalifa Port should engage with national initiatives such as Operation 300bn and Make it in the Emirates to ensure its automation objectives complement the UAE's industrial diversification goals. Such alignment will position the port as a critical enabler in the country's broader economic transformation and innovation-driven growth.

To translate strategic opportunities into actionable initiatives, Khalifa Port could launch several targeted pilot projects and partnerships. For emerging technologies, the port may pilot a blockchain-based documentation system in collaboration with Maqta Gateway and UAE Customs, and trial autonomous trucks within the KIZAD corridor through partnerships with companies like Einride or Navya. Additionally, drone-based inspection and delivery pilots could be conducted with local UAV startups, while predictive analytics capabilities could be integrated into terminal operations via collaborations with AI firms such as Palantir or SAS. On a regional and global scale, Khalifa Port could establish a PortTech Innovation Lab with major tech firms like IBM, Siemens, or Huawei to co-develop smart port solutions, and initiate a digital trade corridor pilot with regional ports such as Jebel Ali or Sohar to streamline cross-border logistics. In the sustainability domain, the port could retrofit part of its equipment fleet in partnership with ABB or Schneider Electric to support electrification, and work with certification bodies like DNV or Bureau Veritas to obtain environmental standards such as ISO 14001. For economic diversification, Khalifa Port could co-develop an automated e-commerce logistics hub with Amazon, Alibaba, or noon.com, and collaborate with logistics leaders like Agility or DHL to implement a cold chain automation project featuring smart, temperature-controlled storage systems.

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