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The Arab Institute of Navigation is pleased to open this issue of its academic journal by highlighting a landmark achievement for the Arab maritime community: the election of five Arab states to the Council of the International Maritime Organization (IMO) for the 2026–2027 term. The United Arab Emirates has been elected under Category B, representing major maritime nations, while the Arab Republic of Egypt, the Kingdom of Saudi Arabia, the Kingdom of Morocco, and the State of Qatar have secured seats under Category C, representing countries with special interests in maritime transport. These elections, held during the 34th session of the IMO Assembly in London, reflect growing international recognition of the Arab world's expanding role in global maritime affairs.

This development carries particular importance at a time when the international maritime sector is undergoing profound transformation. Issues such as decarbonization, digitalization, maritime safety, environmental protection, and supply chain resilience are reshaping the priorities of global shipping and port management. Membership in the IMO Council places Arab states at the core of these discussions, enabling them to contribute directly to shaping international regulations, policies, and strategic frameworks that will define the future of maritime transport.

For the Arab world, this achievement is the result of sustained investment in maritime infrastructure, institutional capacity, and human capital. Over recent decades, Arab countries have developed world-class ports, logistics platforms, and maritime corridors that connect major global trade routes. Strategic maritime assets such as the Suez Canal, major Gulf ports, and advanced logistics hubs in North Africa and the Arabian Peninsula have positioned the region as a central pillar of international trade and maritime connectivity. These developments have enhanced the competitiveness of Arab maritime economies and strengthened their integration into global supply chains.

Equally important is the Arab region's growing commitment to maritime safety, security, and environmental stewardship. Arab states have made significant progress in implementing IMO conventions, improving port state control, enhancing maritime education and training, and adopting modern technologies to ensure safe and secure navigation. Their increasing engagement with environmental regulations, including emissions reduction and marine environmental protection, demonstrates a clear alignment with global sustainability objectives.

The presence of multiple Arab states on the IMO Council also strengthens regional coordination and collective influence. It creates opportunities for aligning positions on key regulatory issues, sharing best practices, and supporting the interests of developing maritime nations. This collective representation enhances the Arab voice within international maritime governance and contributes to more balanced and inclusive decision-making processes.

For the academic and professional maritime community, this milestone reinforces the importance of research, education, and policy-oriented dialogue. Institutions such as the Arab Institute of Navigation have a vital role to play in supporting this momentum by advancing scientific research, fostering professional development, and contributing evidence-based insights to maritime policymaking at national, regional, and international levels.

As the opening article of this academic journal, this editorial underscores a central message: the election of Arab states to the IMO Council for 2026–2027 is not only a diplomatic success, but also a reflection of the Arab world's maturity as a maritime actor. It signals a transition from participation to leadership, and from regional significance to global responsibility. The Arab maritime sector is increasingly positioned to contribute to a safer, more efficient, and more sustainable international maritime system—an objective that lies at the heart of both global maritime governance and the mission of this journal.

Autonomous Ships: Challenges and Solutions, Facing the Regulatory System

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المستخلص

في السنوات الأخيرة، ازداد الاهتمام بتصميم السفن الذاتية القيادة بشكل كبير. وقد جاء هذا الاهتمام نتيجة للتطور السريع في التكنولوجيا، واستلهامًا من التكيف الحديث للأنظمة الأوتوماتيكية والذاتية التشغيل في وسائل النقل المختلفة. ومن هذا المنطلق، يمكننا أن نتساءل عما إذا كان من الممكن تطبيق هذه التقنيات في قطاع الملاحة البحرية. إن التقدم نحو الابتكارات المتطورة أمر لا مفر منه، على الرغم من العقبات التي تظهر في كل مرحلة من مراحل التطور.

ومن هذا المنطلق، لا يمكن تجاهل التحول التكنولوجي القادم في القطاع البحري، والذي يجب الاستعداد له والتعامل معه. تناقش هذه المقالة الاتجاهات الحالية في تطور السفن الذاتية القيادة، بالإضافة إلى استعراض بعض المبادرات العالمية الحديثة. كما تبحث الدراسة في التأثيرات المنفصلة والمشتركة للسفن السطحية البحرية الذاتية القيادة (MASS) على الابتكارات، والقوانين، والصناعات، في ضوء التحول الجديد في النموذج البحري، وذلك من خلال استخدام استبيانات وتحليل بيانات نوعية وكمية بمشاركة خبراء وموظفين من القطاع البحري.

وفي الختام، توصي المقالة بضرورة اعتماد نهج شامل لبناء التكنولوجيا والإطار التنظيمي، والتأكيد على أن التواصل والتعاون بين مختلف الأطراف المعنية على أساس التفاهم المتبادل يعد أمرًا أساسيًا لضمان دخول السفن الذاتية القيادة إلى صناعة النقل البحري بنجاح. وتخلص المقالة إلى أن هناك نقصًا في جاهزية الاتفاقيات البحرية والموانئ والمعاهد البحرية لتطبيق آلية السفن الذاتية التشغيل في الوقت الراهن.

Abstract

In recent years, interest in autonomous ship conception has grown considerably. Inspired by the latest adaptation of automated and autonomous systems in different means of transportation and due to the swift technological development, we could question wither and if these technologies could be implemented in the maritime business or not. Progress toward cutting-edge innovations is inevitable notwithstanding the obstacles that develop throughout every evolution. Acknowledging that, one can't ignore the upcoming technological transition in the maritime sector, which must cope with and prepare for. The present article debates the current trends in the evolving autonomous ships as well as reviewing some of the latest global initiatives. Furthermore, the research looks into the separate and combined implications of marine autonomous surface ships

(MASS) on innovations, laws, and industries in light of the novel maritime paradigm change, by using questionnaire form and analysis with qualitative and quantitative data with different expertise and maritime sector employees participant .Finally, it is advised that holistic approaches to building the technology and regulatory framework be used and that communication and cooperation among various stakeholders based on mutual understanding are essential for the MASS to arrive in the maritime industry successfully .The article finds that, there is lack of readiness of maritime conventions , seaports and maritime institutes to implement the mechanism of automated ships at the present time.

Keywords: MASS, IMO, autonomous shipping, maritime law, Maritime Safety Committee, advanced sensor module, shore control center, cyber security threats.

1- Introduction

Ships are considered the largest manmade machineries ever. Newer ships are enormous, totally automated and state of arts. The shipping sector calls for superbly qualified seafarers, particularly seafaring officers in order to manage such modern ships both effectively and securely.

Throughout the 1980s, one of the important challenges within the maritime sector was crewing. Numerous investigations, for instance, the BIMCO ISF Manpower Report 2005 2010, 2016 and 2021 seafarer workforce report have highlighted an alarming seafaring officers' shortage. According to the BIMCO/ISF Sea Force Work Report 2021, estimates for shortage in seafaring officers will be 97,000 in 2020 and to be 147,500 within 2025. This situation demands the program revising along with its subjects in order for better preparation of seafaring personnel for their future tasks in addition to encouraging the young generation to enroll into the seafaring schools. The Germanischer Lloyd and Fraunhofer CML (2014) carried out a huge-scaled investigation that involved 100 ship administration businesses worldwide to determine what they have implemented for their business processes improving and what are their considerations for best practices in the sector. These organizations indicated that their major issues ship management in the med-term are to be among five domains as follows: crewing (88%), technical management (62%), financial management (50%), safety and quality (27%), and procurement (12%).

Both reports of Pourzanjani in 2002 and Schroder in 2004 have highlighted that challenges facing crewing comprise not only of the quantity. There are also lack of well qualified seafarers at different levels of seniority and quality. Also, at diverse seniority levels, there is a significant shortage of sufficiently trained seafarers. In the early 1970s, the IMO (International Maritime Organization) initiated a research to create international guidelines for seafarers which help improving the seafarers' quality. IMO's Standards for Training, Certification and Watchkeeping (STCW) describes the globally documented standards for the on board crew. The STCW competencies code are mostly centered on both the management and technical abilities along with long-termed practical at-sea training investigations. STCW is regarded as the principal reference for maritime education and training (MET). In 2011, a significant revision was implemented to the STCW which necessitated the change of MET programs as well. This change resulted in the diversification of MET training courses, MET programs' establishing and expansion, collaborations between MET and shipping businesses, and the competitiveness of students and trainees in various MET programs. Institutions of MET ought to maintain surveillance out for such (Yongxing and Ruan, 2009). As a unique area, MET encompasses to meet with the international standards besides national vocational qualification necessities. English is the maritime industry's lingua franca, and seafaring officers must have excellent English language skills. According to Demydenko (2012) 'Maritime English as an international Language and Lingua Franca is solidly believed to be the global language of the sea'. This fact makes MET's design and delivery very complex that it necessitates more detailed evaluation.

In their paper, Porathe et al. (2014) have presented four primary arguments for how autonomous shipping is thought to be an achievable choice as follows: (1) initiatives to lower transportation expenditures; (2) the demand for workers to have improved working conditions while on board and to prevent future shortages of seafarers; (3) the necessity to reduce the emissions globally; and finally, (4) the requirement to improve the maritime safety. According to a submitted report to IMO in 2010 by the International Shipping Federation (ISF) and the Baltic and International Maritime Council (BIMCO), the maritime sector is anticipated to confront constrained recruiting markets, including continuous shortages of vessel officers (Lang, 2010). The maritime sector has witnessed excess capacity and freight rates, because of the dangerous circumstances at work and the extended durations spent off the coast, under the very challenging scale economics.

The paper depends on clarifying the challenges on implementing the autonomous ships on maritime regulatory and theoretical concept based on maritime institute by using questionnaire panel analyzed by statistical software, such as SPSS to describe strength and weakness for implementation.

2- Literature Review

The literature on autonomous systems implementation in commercial vessels has grown significantly since the late 2000s in accordance to Munim (2019). According to Budak and Beji, 2020, The results obtained from those studies reveal promising data, emphasized that smart ships could be the future of the maritime industry numerous papers and case studies on remote control, maneuvering of autonomous ships and navigation has contributed to the present body of literature. Their findings provided encouraging data, indicating that smart ships represent the next phase of maritime businesses, modernizing vessel design methodologies and commercial vessel procedures. Besides this knowledge, it was expected that the autonomous systems integration into the marine transportation might generate an all-inclusive transformation not just within marine navigation but also in the whole marine sector, from vessel building to logistic activities and even ship recycling (Gu et al., 2021; Kafali et al., 2022).

It is essential to do cutting-edge research for the change from the conventional transportation to the MASS to become a reality. Numerous novel projects have provided a firm technical foundation for an autonomous marine environment. As an illustration, in the EU, the AUTOSHIP project has advanced the driving force for autonomous ship research. The project objective was to compete with land transport in the inland watercourses and coastal short-sea shipping by means of technical knowledge and advanced technology (Bolbot et al., 2020). Additionally, the AEGIS project has presented a secure and competitive design of a maritime logistical system for the EU through the integration of autonomous vessels and automated cargo handling technologies (Psaraftis et al., 2023). These two projects findings have indicated the significance of reliability and trust of autonomous systems according to Rødseth and Wennersberg (2023).

Based on the previous literatures, the autonomous project facing unseen prospects problems since the implement is not success yet in logistics activities and also for technical issue that leads us to the fact that the regulatory paradigm is not guided yet.

3- Challenges and Solutions

3.1 IMO Regulatory

Regarding regulations, the IMO determined to perform a regulatory scoping exercise (RSE) in order to evaluate MASS's safety, security, and environmental performance (IMO, 2022). On the other hand, the RSE may be a challenging matter, since it might cover a variety of subjects, for instance security, safety, port contacts, marine environment and pilotage in the event of an emergency. Furthermore, the international maritime conventions including SOLAS (the International Convention for the Safety of Life at Sea), COLREG (the International Regulations for the Prevention of Collisions at Sea), and STCW of Watch-keepers are all applicable to MASS. Therefore, IMO Member States will be requested for reviewing their domestic laws' scope taking the RSE in consideration.

Utilizing a cutting-edge information and communications technology (ICT) systems would enhance the vessels' control skills, communications, and interactions. Therefore, ships shall soon be controlled by land-based or remote offshore services (DNV and GL 2022). Autonomous vessels have been successfully used for aeronautical, military, and investigational objectives. Also, deep-sea explorations employ submersible automated vehicles, including autonomous underwater vehicles (AUV) and remotely operated vehicles (ROV) that are currently in development. Nevertheless, in terms of efficiency, safety and environmental sustainability, innovation that substitutes staffing must surpass personnel (Komianos, 2018).

On the manufacturing sector, autonomous cars are already being created for a variety of transportation means, including automobiles airplanes, and trains. Thus, MASS is predicted to have a substantial impression on ship-building, electronics and equipment as well as shipment and port infrastructures within the marine sector. Furthermore, autonomy, automation, unmanned procedures; enterprise-grade connectivity, huge amounts of data, and analytics will continue to increase within the marine industry (Shahbakhsh, 2022). Accordingly, efficient interaction and collaboration with the main stakeholders, principally in the shipping, ship-building, and port industries, is necessary for a successful implementation of the MASS.

To accurately depict the authors' knowledge, several reviewing researches have thoroughly or briefly explored the regulatory matters concerning MASS. The researchers' interviews and discusses with maritime professionals, including maritime officers, maritime architects, and senior naval engineers, motivated the current research. The current paper has concentrated on all of the inferences that MASS may have on the maritime sector at the humanoid level (both education and training), lawmaking level (the description of regulations and transparent laws), and technological level (e.g. security navigation). This article displays some observations on the challenges and problems that must be addressed promptly; it doesn't work with the collected data by trials, quantified scenarios or calculations. The authors' principal objective is demonstrating the scale of those issues and the effort that still needs to be made to accomplish worldwide secure autonomous surface ship navigation.

This document's structure is as follows: We began by introducing the most recent projects based on worldwide trends to build autonomous watercraft. Secondly, the MASS impact on regulations, technological advances, and businesses, as well as their relationships, has been investigated in order to recognize both past and future initiatives to gear up for the novel marine paradigmatic transition.

3.2 Conventions and Codes to be Changed

Regardless of the rapid growth of technological advancements in the maritime sector, autonomous vessels must undoubtedly comply with global norms in order to safely operate crossways nations and even into the undersea regions that are outside the national jurisdiction. Even though certain aspects of manned-ship regulations, (for example, few clauses of ISM or the International Safety Management Code and their Safety Management Code (ISM)), may be well-matched with the unmanned ships, definitely there is a necessity for exceptional global rules regarding the unmanned ships' characteristics.

3.3 Issue of Laws and Ethics

The business has adopted sophisticated and emerging technology to increase production, reduce expenditures, and improve protection. Regulations and technologies have a mutual influence on each other, thus effective and prompt regulatory processes must exist for the business to fully revenue from the innovation. Conventionally, responsibility was assigned to individuals or organizations which are acknowledged by law, such as shipment businesses. An algorithm doesn't qualify as a moral or formal body; therefore, assigning wrongdoing guilt is meaningless. The matter was comprehensively investigated in the automotive segment. The examination of conventional ethical issues is portion of the debate about the self-driving automobiles safety (Zhang, D 2022). The ISM Code (SOLAS Chapter IX) regulations, such as establishing an official entity responsible for ship safety and avoiding environmental pollution, are going to remain applicable to the MASS (Pundars, 2020).

The progress and usage of autonomous vessels will present various ethical difficulties. Historically, the human communication has governed the shipping processes, but MASS incorporates both man-machine and machine-machine interaction. This risk of implementation or shift evaluation ought to involve an analysis and approaches for situations in which any malfunctions in the machine communication is denied. Liability in law bounds must be identified, notably by establishing realistic criteria and obligation scopes between both the ship-owner and the manufacturers, in addition to an adequate security arrangement for insurance coverage.

3.4 Cyber Security

To guarantee an uninterrupted and secure connection between SCC and the ship in question, precautions must be in place to prevent other parties from intercepting the information transmitted in between. If they are intercepted, the ship's safety is jeopardized since the malicious user could be able to take control of the vessel or obtain a hold of crucial operational data. The paper "Connectivity for autonomous ships" (Gad, 2025;Höyhtyä et al.2017) makes an intriguing recommendation concerning the safety of information. This is the practical application of Blockchain technology. Initially, let us define what Blockchain is and then discuss how it might be utilized in operating the remote vessels. In layman's terms, a Blockchain is a digitalized distributed ledger consisting of information blocks that are constantly updated and verified in real time via a computerized network that contribute to it. As soon as data is submitted on the Blockchain, for instance the remote operator's command to guide the ship to the harbor, it is unchangeable given that the information has been encrypted and uploaded chronologically to the chain. The article "Blockchain Security of Autonomous Maritime Transport" published in 2019 studied how it can be applied to remote operations. The proposal was that all data transported from and to the ship would be stored on a distributed network accessible only to a verified operator. To gain access to the network, users have to first go through a Certification Authority (CA) and be issued a certificate that verifies their identity (see Appendix H) (Petković, Mihanović, and Vujović, 2019).

3.5 Legal Liability

Presently, the master is responsible for a traditional ship's legal responsibility. If something goes wrong, the master is responsible. However, what happens when remote operations and autonomous vessels are put into effect? Who will bear this obligation, and how would it be modified? Current laws do not address remote and autonomously operating scenarios; nevertheless, they can be evaluated and clarified in order to take steps toward covering them. By referring to the Air Traffic Act for autonomous aviation systems under Croatian law, insights can be gained and used to remote marine operations (Ordinance on Unmanned Aviation Systems, n.d.). Additionally, a table released by Kennedys Law in 2018, which outlines the legal responsibility based on the system utilized, can be found later (Delagrange and Pellicer, 2018).

4- Novel Approaches and Technologies within the MET

MET institutes must implement novel innovations and make educational and technological advancements. They must also progress and transfer innovative ideas in their own field of interest.

This is the reason for various international MET platforms to be created, including IAMU (International Association of Maritime Universities), IMLA (International Maritime Lecturers Association), Global MET, METNET, and Mari Future etc. In MET, in terms of the emerging technologies and methods, the objective is not to list these technologies separately, but rather to assemble them conferring to the attained functions. They are as follows: 1) excessive simulator usage for representing the real, 2) life conditions and software that provide enhanced comprehension, 3) highly organized and lecturer-validated long-termed maritime training as an additional advantage to academic classes for cadet preparation to their responsibilities on the shipboard. For example, the engine rooms and the mock-up bridge precisely similar to equipment of navigation and communications. Besides, fully-equipped laboratories can assist students of having their courses leading to better understanding. Also, simulators can facilitate the students to adapt to real systems and equipment in addition to their onboard duties.

Computer-assisted training can be advantageous to students in exploring the delivered subject within the classroom. Furthermore, students can self-assess their own accomplishment along with better evaluation of the available chances for the lecturers. IT support permits the students to communicate with both the online tutors and lecturers. For problems solving, it is imperative for students to be connected with MET institutions during their sea training. Lifelong learning is a vital share of modern daily life that can provide individuals with additional possibilities for learning. E-learning offers an excellent learning and training chances for the seafarers who are very far away from land facilities. Currently, several MET institutions offer e-learning courses for the seafarers and post-graduate course works too.

Efficient utilization of Port State Control (PSC) outcomes alongside the formation of permanent evaluation /validation organizations including EMSA (European Union Maritime Safety Agency) offer an exceptional opportunity for quality assurance for MET institutions. The whole world is now a little village due to globalization. The marine industry is global in scope, necessitating the complete implementation of global treaties. To thrive in the competitive and tough shipping industry, all parties involved have to hold themselves to gold standards rather than settling for the bare minimum. Without an experienced staff onboard the ship, there is no prospect of success. The MET have a crucial role in guaranteeing shipping quality. The only technique for guaranteeing quality in the MET is to constantly improve the system through the progress and transfer of innovation while adhering and integrating the novel innovations.

5- The New Reshape for Maritime Industry

Autonomous ships are transforming the shipping sector through the implementation of new technology, procedures and business models that have the potential of changing how ships are operated today. Autonomous ships advantages include increased efficiency and safety of the ship, data-driven activities, and greater capabilities like autonomous and remote operations.

A. **Improved efficiency and safety:** autonomous ships are equipped with Creative innovations such as machine-learning, the Internet of Things (IoT) and artificial intelligence (AI) which can assist boost vessel operations, increase safety, and lessen the risk of error made by humans.
B. **Data-driven operations:** autonomous ships produce massive amounts of data which are analyzed for decision-making improvement, lower the expenses, and increase safety. Predictive analytics as well as machine learning algorithms can aid in discovering patterns, outcomes' prediction, and vessel operation optimization.
C. **Remote and autonomous operations:** shore-based control centers will be responsible for controlling the autonomous via communications systems and real-time data. These centers can monitor and control movements and navigation of the ship as well as other operational functions. Hence, ships will be operated more efficiently with enhanced safety and reduced expenditures.

Integrating autonomy in the shipping sector is an extended process, with commercial operators adopting autonomous technology in stages. This staged approach allows operators to critically evaluate the technology's advantages and drawbacks along with making any necessary changes to guarantee its successful incorporation into their operations. The future of autonomous ships appears to be rather promising if the obstacles involved with their deployment are sufficiently managed. They have the potential to significantly improve safety and efficiency, minimize operational expenditures, and decrease the environmental impact of maritime activity.

6- Methods and Materials

The survey study was designed to engage graduates from diverse backgrounds, including multiple disciplines, institutions, and regions, as well as varying degrees of understanding of autonomous ships and smart shipping. The most prominent groups were those studying to become future navigators or future electrical engineers and technical officers in the engine department. In this study, researchers provide information about the participants who completed the survey, including gender, age, country of MET graduation, years of marine service, current occupation, and highest level of education. Of the ٢٠٠ participants who returned and correctly completed the surveys, ١٧٨ identified as male and ٢٢ as female, representing 89 % and ١١%, respectively. The majority of participants (٩٢%) fell under the age of 35. The highest number of participants graduated from Egypt (٩٠%), followed by Jordan (٢%) and Saudi Arabia (٨%). CoC holders (٩٨%), while the smallest group represented was trainers (٢%). Holders of COC management level (70%), holder of COC operational level (30%).

Data collected from the questionnaire were analyzed using statistical analysis software, such as SPSS. This tool allowed researchers to perform descriptive statistics, such as frequencies, percentages, means, and standard deviations. The questionnaire analysis consist 10 questions distributed in 5 sections.

Participants were asked to rate their level of agreement with the statements using a five-point Likert scale. A linear scale from 1 to 5 is a common way to measure agreement or disagreement with a statement. This scale allows respondents to indicate the extent of their agreement or disagreement on a scale ranging from "strongly disagree" (1) to "strongly agree" (5), with three possible neutral options in between (2 = "disagree," 3 = "neutral," and 4 = "agree")

Table 1 statistics analysis

Socio Demographics Data	Frequency (N=200)	Percent
Section 1		
Q1. What is your gender?		
Male	178	89%
Female	22	11%
Q2. What age range do you fall into?		
Less than 35 years old	184	92%
More than 35 years old	16	8%
Q3. In Which country did you graduate from the Maritime Education and Training institute (MET)?		
Egypt	180	90%
Jordan	4	2%
Saudi Arabia	16	8%
Q4. What is your current occupation?		
COC management level	140	70%
COC operational level	60	30%

Section 2

- In light of increasing numbers of specialized vessels over general Cargo vessels, autonomous ships are suitable for all commodities types.
- Autonomous ships apply for existing Sea born logistics trade.

Section 3

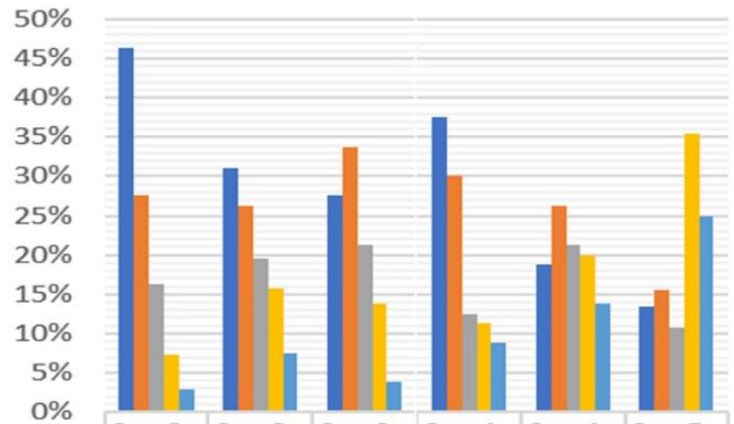
- Autonomous ships have a positive impact on labor skills.

Section 4

- The availability of financial resources to equip maritime institutes is available to all maritime countries.
- Training and certification of seafarers existing adequate for new technology era.

Section 5

- New conventions and regulations will take place with significant changes.



	Sec.2_ Q1	Sec.2_ Q2	Sec.3_ Q1	Sec.4_ Q1	Sec.4_ Q2	Sec.5_ Q1
Strongly Disagree	46%	31%	28%	38%	19%	14%
Disagree	28%	26%	34%	30%	26%	16%
Neutral	16%	20%	21%	13%	21%	11%
Agree	7%	16%	14%	11%	20%	36%
Strongly agree	3%	8%	4%	9%	14%	25%

Figure (1) Survey Study Analysis

As shown in Figure 1 the percentage of responses for each survey question in different sections indicates that IMO Codes and Conventions require considerable modification to suit the MASS requirements.

The highest percentage of disagreement is for question one in section two is an indicator that MASS will not be suitable for all types of ships and lines of trade.

7- Results

Introducing the autonomous shipping will offer the chance to raise the efficiency of ship operations, while also improve sustainability, which is the most significant motivator in any sector (UN, 2008). The development of intelligent vessels would improve the scenario, resulting in an enhanced, more lucrative, and presumably more secure shipment business. Autonomous ships' development is similar to those within the MUNIN project will offer an extensive alternative for the major issues of maritime transport sector, leading to operational expenses decrease, better environmental preserving activities, and minimizing the human effort (Burmeister et al., 2014b). Because of the rapid advancements in science within the maritime sector, this type of ship design is so innovative that no international law or regulation applies to it yet. The IMO hasn't approved this type of ship and hasn't received any proposals from contracting government for regulating autonomous vessels. The widespread adoption of the autonomous ship notion will have a substantial impact on industry efficiency, management of human resources, and preventing accidents. The benefits of environmental protection are equally essential. Although the existing maritime equipment might address all safety, environmental, and commercial issues, the absence of a sufficient legislative structure might postpone the genuine implementation of such vessels.

8- Conclusion

There is an enormous gap between humanity's evolutionary vision and the automation influence on environmental sustainability and human existence. Even more important, automation rebalances authority among all stakeholders and parties in the international laws. The navigation conditions are increasingly becoming challenging and more complex, impacting contemporary life and values in the risk society era. This might be one procedure for rescuing the environment while also ensuring survival and moral sharing among each and every country or population. It is a challenging issue accomplishing that intersects with other subjects in social science, but it will undoubtedly contribute to the solution. Among the greatest obstacles for legislators and all the stakeholders are to design and improve a particular strategy for achieving a balance between both influencing the human situation and the environmental degradation with the automation progression. Finally, the IMO safety Committee should make progress on the development of a goal-based instrument regulating the operation of maritime autonomous surface ships (MASS), which is expected to be adopted by 2025 in different scope pattern to overcome the regulatory challenges on both the legal clauses and seniorities responsibilities on shore base for coastal domestic voyages which is expected to use autonomous ships effectively.

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Extreme Sea Level Analysis and Return Period Estimation Along Alexandria Coast Using Gumbel Cumulative Distribution Functions

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المستخلص
تهدف الورقة البحثية الى تحليل فترة اعادة التكرار لأقصى مستويات لسطح البحر على ساحل الأسكندرية باستخدام نموذج احصائى يعتمد على دوال التوزيع التراكمى لمعادلات جامبل و التى تعمل على ايجاد إطار عملى قوى للتنبؤ باقصى مستويات لسطح البحر و فترة اعادة تكرارها نظرا لأنه من المتوقع زيادة معدلات تكرار اقصى مستويات لسطح البحر خلال العقود القادمة نتيجة لتغير المناخ و زيادة درجة الحرارة المحيطة بالأرض. تم استخدام رادار قياس مستوى سطح البحر خلال هذه الدراسة للحصول على بيانات مستوى سطح البحر كل ساعة باجمالى ١٣٩٨٦ ساعة لمدة ١٩.٣ شهر فى الفترة من ٥ يونيو ٢٠١٨ الى ٩ يناير ٢٠٢٠ ، و قد تبنت هذه الدراسة الإسلوب الكمى التحليلى فى تحليل البيانات وحساب اقصى مستوى لسطح البحر على اساس شهرى للبيانات المرصودة. استخدمت معادلات جامبل فى قياس احتمالية حدوث اعلى ارتفاع لمستوى سطح البحر بقيمة تساوى او أقل من اقصى ارتفاع فعلى تم رصده و تم تطبيق هذه الإحتمالات على اقصى ارتفاع لكل شهر.

تركز الورقة البحثية على حساب فترة إعادة التكرار لحدوث اقصى ارتفاعات لمستوى سطح البحر بما يتناسب مع الفترات القصيرة فى رصد بيانات مستوى سطح البحر، و بالتالى تم حساب فترة إعادة التكرار للمستويات القصوى لسطح البحر بالشهور بدلا من حساب معدل تكرارها بالسنوات. وقد خلصت النتائج الى أن متوسط اقصى ارتفاع لمستوى سطح البحر ٠.٧٧ متر و بالنسبة لأقصى ارتفاعات شهرية تراوحت بين ٠.٦ متر و ١.٠٤ متر خلال فترة الدراسة لمدة ١٩.٣ شهر، وتظهر الدراسة باستخدام معادلات جامبل ان أعلى احتمالات للحدوث تكون مع اقصى ارتفاعات لمستوى سطح البحر مقترنة باطول فترة زمنية لإعادة التكرار بالشهور. و قد القت الدراسة الضوء على اهمية حساب فترات اعادة التكرار لتحقيق لدعم الإدارة الساحلية المرنة، وتقديم خطة دقيقة لتقييم المخاطر مع رؤية واضحة لإحتمالية تعرض مدينة الإسكندرية لتكرار المستويات القصوى لمستوى سطح البحر بمعدلات عالية في المستقبل القريب.

Abastract
The study Analise the return period of extreme sea levels at Alexandria coast with a different approach of statistics model, the cumulative distribution function method based on Gumbel equations provides a robust framework in statistics of extreme sea level prediction and recurrence

estimation. Return period of extreme sea level heights are expected to occur more frequently in the next decades influenced by climate change and global warming. The study utilizes sea level radar hourly data, with total 13,986 measurements over 19.3 months, between18th of June 2018, to 9th of January 2020. The study methodology underpinning an analytical quantitative method to analyze observed data and determines the monthly extreme sea level value in random data. The Gumbel distribution measures the probability F(x) for each extreme sea level X to be equal or less than this value. The study focuses on the methods to estimate return period for short term of data observation; however, the study estimates the return period for extreme sea level in months instead of usual estimation in years. The results revealed that the average extreme sea level in Alexandria is 0.77 meters, with monthly extreme sea level range between 0.6 to 1.04 meters. The findings highlight the highest probability of occurrence concurrently with the highest sea level value and has the longest return period in months.

The study shed the light on the short pattern intervals of extreme sea level recurrence to support resilient coastal management, and precisely present risk assessment plan with clear vision to how far could Alexandria vulnerable to adverse conditions in near future.

Keywords: Return period; Extreme Sea level; Alexandria coast; Cumulative distribution function, Gumbel method.

Introduction

Climate change, Global warming, and consequently Sea level rise (SLR) are drivers to flooding, coastal erosion, and ecosystems deterioration. The 2023 IPCC assessment report revealed that sea levels could rise up to 2 m by year 2150, and between 3 m and 7 m by 2300 (Büyüksalih and Gazioğlu, 2024).

Extreme events and climate change could lead to hurricanes and typhoons in many areas in the world recognized by warmer ocean temperatures; causing widespread destruction (Griggs and Reguero, 2021).

Low-lying coastal areas face significant risks from inundation due to extreme sea levels (Baldan et al., 2023). Alexandria, as a low-lying city, is particularly vulnerable to these dangers. Globally, communities, critical infrastructure, and essential socio-economic assets are becoming increasingly vulnerable to coastal flooding (Oppenheimer et al., 2019; Andrée, 2022). Although tides in Alexandria typically exhibits a very short range, during special events, extreme sea levels often occur, particularly during spring tides. Storm surges significantly contribute to these events, playing a major role in SLR (El-Geziry and Dabbous, 2021). Observations indicate that extreme sea levels have increased over the last century in various regions, resulting mainly from variations in sea level rather than significant changes in storm surge parameters (Menéndez and Woodworth, 2010)

Future hazard scenarios project that the mean sea level (MSL) will rise by 14 cm by 2030, which is sufficient to inundate 15% of Alexandria (Noby et al., 2022b).

As SLR is expected to have a significant impact on the beaches of Alexandria, with projections indicating a loss of 16.13% of the current total beach area by 2100 based on the mean value of SLR. The variations in extreme sea levels are influenced by both SLR and changes in storm surge activity. However, storm surges specifically contribute to extreme sea-level events, as they result solely from storms (Calafat et al., 2022).

The graphs in Figure (1) and Figure (2) track respectively the change in global sea levels since 1993 and changes in sea level from 1900 to 2018, based on satellite observations, As Figure (1) provides real-time data showing the steady increase in sea levels as global temperatures rise indicating the current rate of sea level rise is approximately 3.3 mm/year. This rate has been accelerating over last century, driven by the combined effects of melting ice sheets, glaciers, and the thermal expansion of seawater as the planet warms, While Figure (2) demonstrates various factors influencing sea level changes from 1900 to 2018, marked with pluses (+) for those contributing to the rise (like ice melting and thermal expansion) and minuses (-) for those contributing to sea level decrease (NASA, 2025).

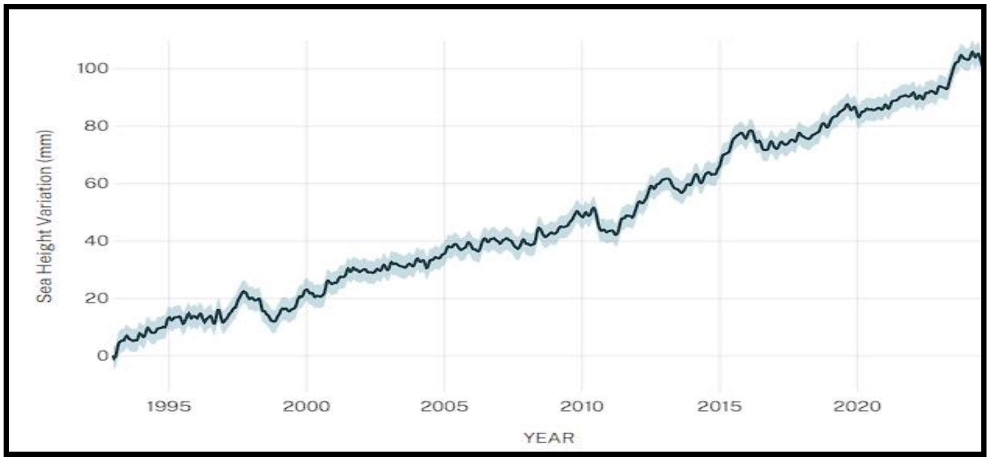

Figure (1) Changes in Global Sea Level since 1993 (NASA, 2025)

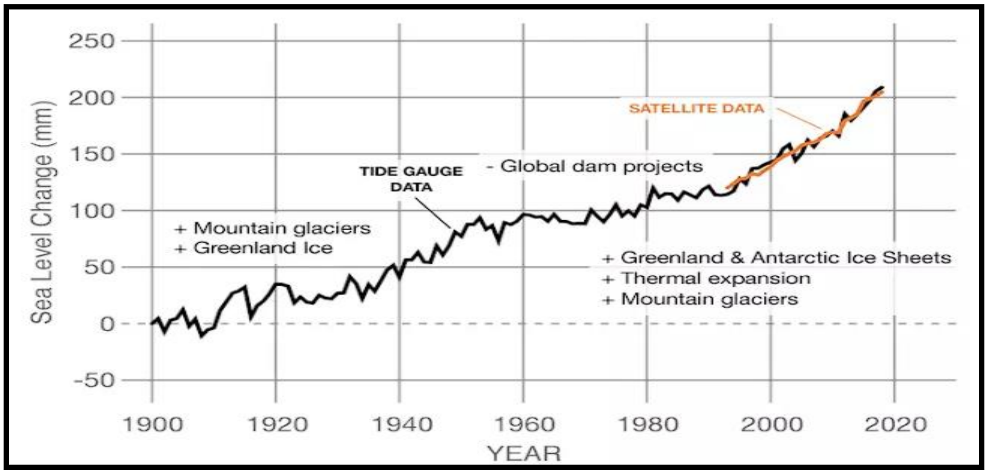

Figure (2) Changes in sea level from about 1900 to 2018 (NASA, 2025)

Both Figures are shown according to the time period when they were most active in affecting global sea levels. This helps illustrate the gradual but persistent trend of rising sea levels over time (NASA, 2025).

The design of maritime and coastal structures requires consideration of extreme waves and extreme sea levels. These extreme conditions may occur only once within a specified period, known as the recurrence time of the extreme sea level height (Goda, 2010).

This recurrence time can be estimated through analysis by applying one of three methods: (Goda, 2010)

a) Cumulative distributions function or total sample method used to fit an appropriate distribution function.
b) The maxima method selects the highest values in a total period division (e.g. years in a number of years).
c) The Peaks-Over-Threshold method focuses on analyzing peak values that exceed a specified threshold.

The annual maxima method is mostly used in extreme flood discharges, while peaks over threshold (POT) method, typically has relatively substantial data volume but with low range of confidence intervals.

The Cumulative distributions function method present the probability of continuous random variable X with values between two distinct numbers as minimum and maximum values (A and B) to be equal or less than a specific value x, however the formula could be expressed as $F(x) = \Pr(A \leq X \leq x]$ (Goldstein, et al., 2010).

The Cumulative Distribution Function method utilizing the Gumbel distribution for extreme sea levels exhibited high consistency with empirical distribution. Moreover, the Gumbel distribution is regarded as one of the most important statistical tools for analyzing extremes in hydrology and flood.

The return period and risk assessment of extreme sea level at Alexandria coast, particularly at Abu-Qir Bay, demonstrate that extreme sea levels and risk of flooding could reach to extreme flooding risk. Data Analysis of water level measurements over 21 years (1990–2010) shows that the highest probabilities for sea level levels within range between 45 cm to 60 cm (El-Geziry and El-Wakeel, 2023). Extreme sea levels indeed influenced by different factors such as seasonal variations and long-term trends, making them oscilate from year to year. New studies indicate that sea levels are usually changing, and consequently, extreme events impact coastal areas, recurring at intervals determined by their return period (Macpherson et al., 2021). Extreme sea levels in Alexandria have been calculated with their return periods: The sea level of range 165 cm is expected once every 100 years, while 181 cm could be occurred once every 500 years (Said et al., 2020). Risk assessment of extreme sea-level rise is the clue in designing vital coastal structures and estimate their expected lifespan (Said et al., 2020). Between several methods assigned for long return periods estimation, some involve numerous uncertainties, especially when large amounts of data are filtered out of calculations. Average Conditional Exceedance Rate (ACER) method is a reliable approach as it utilizes the entire dataset in its analysis, and presents better accuracy compared to traditional techniques. Unlike conventional methods that often rely on extreme value analysis leading to the Generalized Extreme Value (GEV) distribution, the ACER method estimates the three essential GEV parameters: location, scale, and shape. This method provides a more comprehensive analysis of return levels over long periods (Ryden, 2024).

CDF method Provides a comprehensive representation of the probability distribution, capturing the entire range of values, it requires fitting a statistical model to the data, which may introduce errors if the model assumptions include errors.

Data and Methods of Analysis

The study adopts a quantitative analytical approach, utilizing observed sea level heights referenced to the chart datum of Alexandria Western Harbor (AWH). Sea level measurements were obtained using a CS475A radar sensor installed inside the Harbor at coordinates (31°11'55.55"N, 029°52'22.10"E) as shown in Figure (3). The dataset is of high quality and reliability, with negligible observation gaps, Figure (4) illustrates the standard deviation graph for the observed sea level data collected in AWH. Any missing data, which amounted to only a few hours over the entire period, were mathematically interpolated.

Figure (3) Alexandria coastline with Sea level Radar position in AWH Plan (Google Earth)

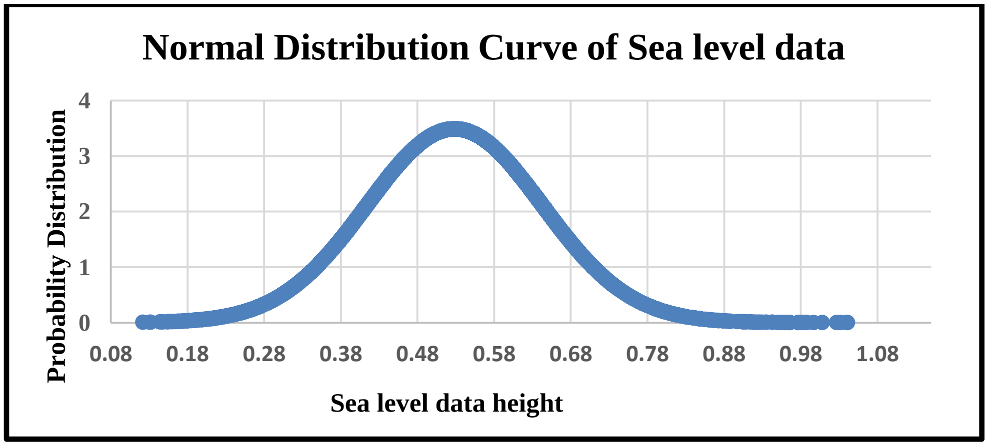

Figure (4) Normal Distribution Curve of Sea level data

The calculation of return periods is a crucial aspect of risk assessment and prediction, however the estimation of the likelihood of recurrence of extreme sea level relies on the best fit method for data distribution and the related parameters to this distribution (Wolski, et al.,2025). Traditional methods for estimating long return periods often involve significant uncertainties, particularly when large portions of data are excluded from calculations (Pugh and Woodworth, 2014).

The analysis of wave heights along the Estonian coast using the Gumbel distribution resulted in a satisfactory alignment with theoretical models and is effectively utilized for accurate predictions of extreme values (Wolski et al., 2025).

The average recurrence interval (ARI) for extreme sea levels can be calculated for different thresholds, with higher sea levels corresponding to longer ARIs through the following formulae (Pugh and Woodworth, 2014).

For a given extreme sea level with a specific (ARI) at any coastline, there is a 37% probability of no occurrences (1/e = 0.367), a 37% probability of one occurrence, 18% probability of two occurrences, and 6% probability of three occurrences during the design period (Pugh and Woodworth, 2014).

The probability of no exceedance (x=0) within a specified design period is determined using the formula: $F=1-\exp(-N)$ ………… (1)

While Direct Exceedance Probability is one of the most widely used return period methods that measures the possibility of a storm surge could be exceeded within a given time frame. This method applies direct exceedance probability (P) for different extreme sea levels, and the return period T in years calculated using the equation as inverse of exceedance probabilities (Coles, 2001). It calculates probabilities conservatively, assuming independence for each division of time (e.g., year or month). The probability Q(z) represents the likelihood of sea level exceeding a threshold value z (Pugh, 2004).

Return period = $\frac{1}{Q(z)}$ ………… (2)

The recurrence probability of a specific sea level, z, denoted as Q(z), corresponds to the annual exceedance probability for that threshold. The return period, also known as the Average Recurrence Interval (ARI), and calculated as the inverse of the exceedance probability (Vogel, 2015). However, this approach relies on precise estimates of the exceedance probability, which can be difficult to obtain in cases of limited data or non-consistent conditions. Recurrence interval or return period calculates the probability of exceedance (P) by applying the equation (Paugh, et al. 2014):

$T = \frac{1}{P}$ …………… (3)

The Cumulative Distribution Function (CDF) utilizes cumulative probabilities F(x) to provide a more comprehensive view of the data, especially when there are variations in extreme sea levels, used for calculating the probabilities of extreme sea levels involves distinguishing between tidal frequency and surge frequency (Abdelhamed, 2024 ; Goda, 2010). The CDF describes the probability that a variable will take a value less than or equal threshold, the return period is calculated based on the calculation of the CDF.

The calculation of the return period for extreme sea levels using Gumbel equations relies on significant statistical parameters, such as the spread of the data distribution, location parameter, standard deviation, and the observed sea level extremes. These parameters depicts the characteristics of sea level extremes. The return period parameters of the Gumbel equations precisely calculate the mean and standard deviation of monthly extreme values over the total 20 months of sea level observations.

Results And Discussion

Sea level data, represented graphically as a normal distribution curve (Figure 5), shows that the most frequently occurring sea level values are centered around the mean sea level. This mean sea level has been accurately calculated using T-Tide software. The data indicates that the most common sea level values fall within the range of 0.5 to 0.55 meters, with these levels recorded 2,445 times during the observation period.

The data set consists of 13,986 hourly sea level records collected over a span of 20 months, providing a comprehensive basis for analysis. To analyze the data statistically, the mean of the monthly extreme sea levels, represented as $\overline{x}$

$$\overline{x} = \frac{1}{M}\sum_{i=1}^{M} xi \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where M is the total number of months

xi represents the extreme sea level value for month i.

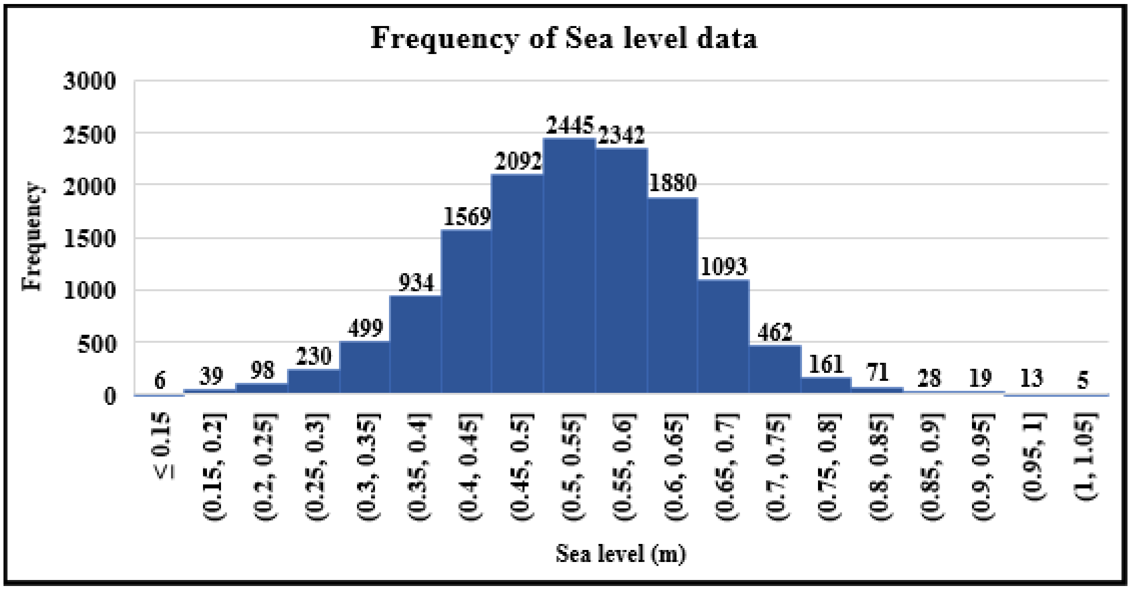

Figure (5) Sea level data represented as normal distribution curve

Using this formula, the mean extreme sea levels ($\overline{x}$) was found to be 0.771 meters, which indicates the average extreme sea level during the observation period. Additionally, the standard deviation (s) of the extreme sea level data was calculated to be 0.09798. The standard deviation measures how much the extreme sea level values deviate from the mean. A relatively small standard deviation like this suggests that the extreme values are relatively close to the mean, indicating consistency in the observed extremes over the 20 months.

The Gumbel equations used to estimate the return period for monthly extreme sea levels as follows: (Zaiontz, 2025)
The spread of data distribution calculated by formulas

β = Scale parameter (Zaiontz, 2025)

a) Scale parameter (β)

$\beta = \frac{s.\sqrt{6}}{\pi}$ ……………………… (5)

β = 0.0764

b) Location parameter (μ)

$\mu = \text{mean}(x) - \gamma\, \beta$ ………………. (6)

where:

γ = The limiting difference between the harmonic series and the natural logarithm (Euler – Maschroni) constant (approx. 0.5772)

μ= 0.72645

The probability of recurrence of extreme sea level is calculated by

$F(x) = \exp(-\exp\left(-\frac{x-\mu}{\beta}\right))$ …………….. (7)

Return period (T) = $\frac{1}{(1-F(x))}$ …………... (8)

Table (1) Return period for maximum monthly Sea level in Alexandria

Date	Max. Sea level	$(x - \bar{x})$ ^2	Probability F(x)	Return Period (T) (Months)
Jun-18	0.715	0.00309	0.313	1.455
Jul-18	0.803	0.00105	0.693	3.254
Aug-18	0.74	0.00093	0.433	1.763
Sep-18	0.81	0.00156	0.715	3.513
Oct-18	0.706	0.00417	0.271	1.371
Nov-18	0.755	0.00024	0.502	2.010
Dec-18	0.819	0.00235	0.742	3.883
Jan-19	0.873	0.01050	0.863	7.321
Feb-19	0.753	0.00031	0.493	1.974
Mar-19	0.609	0.02610	0.010	1.010
Apr-19	0.651	0.01429	0.068	1.073
May-19	0.603	0.02807	0.007	1.007
Jun-19	0.734	0.00134	0.007	1.007
Jul-19	0.802	0.00099	0.689	3.219
Aug-19	0.791	0.00042	0.651	2.863

Sep-19	0.752	0.00034	0.489	1.956
Oct-19	0.824	0.00286	0.757	4.108
Nov-19	0.873	0.01050	0.863	7.321
Dec-19	1.041	0.07314	0.984	61.888
Jan-20	0.757	0.00018	0.511	2.047

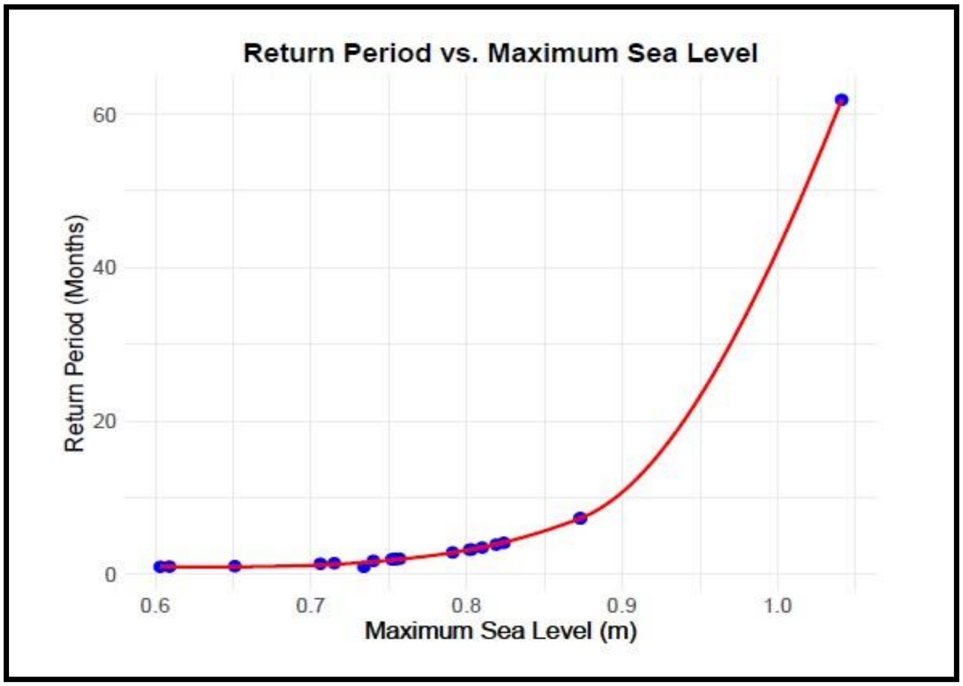

Figure (6) Return Period of Alexandria Harbor using Cumulative Distribution Function

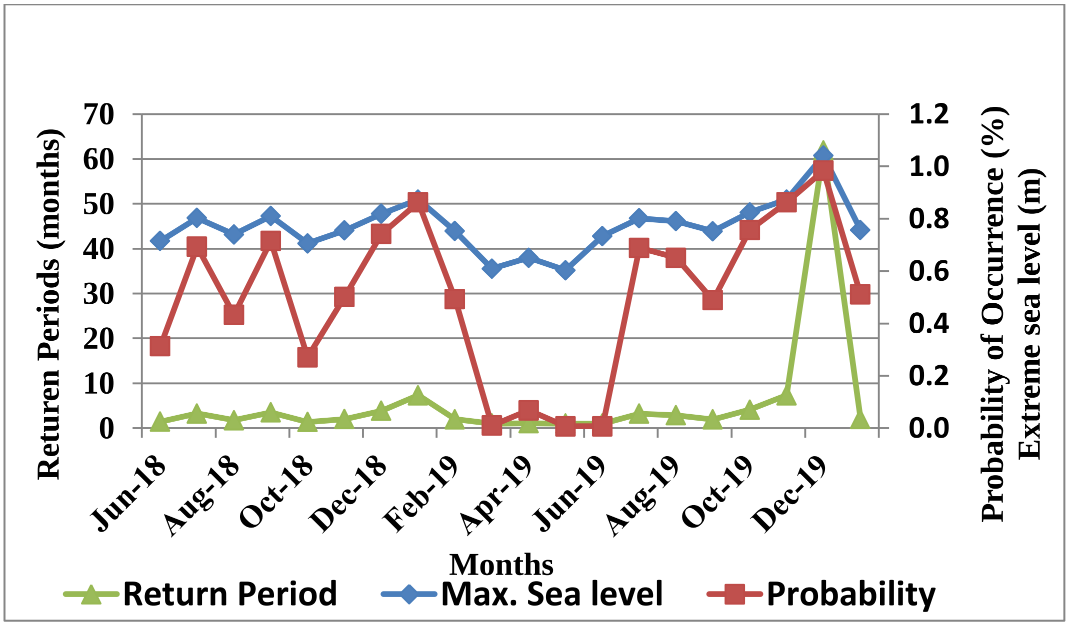

Figure (7) Extreme Sea Level Analysis: Probability of Occurrence and Return Period

The results highlight a critical relationship between extreme sea level events, their probabilities of recurrence, and return periods in months. The findings suggest that the highest extreme sea level, measured at 1.04 m, is associated with a very high probability of recurrence (98.4%) and a relatively long return period of 61.88 months.

The results revealed that extreme events may occur with moderate frequency. Typically, the highest value (1.04 m) is associated with the lowest probability and the longest recurrence period. However, in this study, applying the CDF method resulted in a high probability of 98.4%, corresponding to a return period of 61.88 months for extreme sea levels of 1.04 m or less. This indicates that the probability F(x) represents the proportion of observed values that fall below or equal to the specific threshold of 1.04 meters.

On the other hand, the lowest extreme sea level, at 0.609 m, is associated with a low probability of 1% and a short return period of 1.01 months. This indicates that while such low levels are rare in probability terms, they occur frequently over time.

Conclusions

This study emphasizes the calculation of return periods in short-term intervals measured in months, contrasting with most return period studies, which typically use years.

The analysis of extreme sea levels in Alexandria, performed using the cumulative distribution function (CDF) with Gumbel distribution equations, is a non – traditional approach for return period calculations. However, this method present an appropriate fit for extreme statistical datasets. The results revealed consistent and precise return periods ranging from 1 to 61.9 months, and the potential for achieving high-accuracy results despite the short duration of data observations.

Predictions of extreme sea level heights and their frequency of reoccurrence, as highlighted in the 2023 IPCC report, suggest an increase by 20 to 30 times. The mean extreme sea level during the 20-month study period, calculated at 0.77 meters, exceeds the mean sea level in Alexandria by more than 0.25 meters. This underscores the significant impacts on coastal areas during storms and gusty winds associated with extreme sea levels, highlighting the importance of resilience planning for the anticipated increase in both frequency and recurrence of extreme events.

The findings stress the necessity of continuous sea level data observations to enable comprehensive analysis and precise predictions, which are critical for effective coastal management and risk assessment in Alexandria's near future.

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Hazard Identification in Offshore Rigs Operation

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المستخلص

تُعدّ صناعة النفط والغاز أساسيةً لنمو الاقتصاد العالمي. ومع ذلك، تُواجه هذه الصناعة مخاطر جسيمة تُهدد الحياة. فعلى مر السنين، أُبلغ عن العديد من الحوادث والوفيات في مواقع الحفر البرية والبحرية، ويعود ذلك إلى حد كبير إلى عدم كفاية لوائح الصحة والسلامة وتدابير الوقاية. وعلى الرغم من بعض التقدم المحرز في السيطرة على نسبة ضئيلة من هذه المخاطر في السنوات الأخيرة، إلا أن طبيعة مهنة الحفر، التي تتسم بعدم القدرة على التنبؤ بها، لا تزال تُشكّل تحديات كبيرة لضمان السلامة. تقتصر الدراسة الحالية على تحديد مخاطر تشغيل منصات الحفر البحرية، استنادًا إلى تقارير الحوادث التي وقعت في جميع أنحاء العالم، خلال الفترة الزمنية من عام ٢٠١٠ إلى عام ٢٠٢٤. ويهدف هذا البحث إلى تحديد وتصنيف سيناريوهات المخاطر المرتبطة بتشغيل هذه المنصات، وترتيبها وفقًا لقيمة مخاطرها باستخدام نموذج رياضي مناسب. كما حدد البحث أساليب للحد من عوامل الخطر المتعلقة بالسلامة والصحة التي تواجه هذه المنصات. استُخدمت المنهجية الوصفية التحليلية لتحقيق الهدف المذكور، واستُخدمت حزمة برمجيات مناسبة لتحليل هذه البيانات إحصائيًا، ونموذج مناسب لاتخاذ القرارات متعدد المعايير (MCDM) لتصنيف سيناريوهات المخاطر. وُضعت وناقشت عوامل الارتباط بين عناصر عوامل الخطر.

الكلمات الرئيسية : عمل الحفارات البحرية، سيناريوهات المخاطر، عوامل الخطر، إدارة المخاطر، AHP.

Abstract

The oil and gas industry are crucial to the growth of the global economy. However, this industry is fraught with significant life-threatening risks. Over the years, numerous accidents and fatalities have been reported at both onshore and offshore drilling sites, largely due to insufficient health and safety regulations and prevention measures. Despite some progress in controlling a small percentage of these risks in recent years, the inherently unpredictable nature of the drilling profession continues to pose substantial challenges to ensuring safety.

Where Hazard: something that can cause harm. And Risk: the chance that harm will occur and how bad it could be.

The current study is limited to hazard identification of offshore rigs operation, based on reports on accidents that occurred all over the world, within the time span from 2010 to 2024.

The aim of this research was to identify and classify the hazard scenarios associated with operating these platforms and to arrange the scenarios according to their risk value by using an appropriate mathematical model. It also identified methods to reduce the safety and health risk factors which face these rigs. The analytic descriptive methodology was used to achieve the aforementioned aim, a suitable software package was used to statistically analyze this data and a suitable Multi-Criteria Decision-Making (MCDM) model was used to rank the hazard scenarios. Ranking correlation factors between elements of risk factors were developed and discussed.

Keywords-Offshore Rigs Operation, Hazard Scenarios, Risk Factors, Risk Management, AHP.

1- Background

Oil and gas projects are prime examples of industrial ventures that stand out due to their unique nature. These projects require highly qualified, specialized, and experienced contractors who must possess advanced technological and technical expertise. (Noort et al., 2019)

Additionally, contractors must have a thorough awareness, understanding, and the capability to evaluate all types of risks associated with such complex operations. However, this operation is closely linked to life-threatening risk for drilling crew. (Niven & McLeod, 2009) Over the decades, hundreds of accidents and fatalities have been recorded at onshore and offshore drilling sites, primarily due to insufficient health and safety regulations and preventive measures. (Duvillard, et al., 2021) Despite some progress, the unpredictable nature of the drilling profession has allowed only a small percentage of risk factors to be controlled in recent years. To address this, an extensive and systematic literature review will be conducted to identify the most significant safety and health risks and the root causes of accidents and injuries in offshore drilling over the past 14 years, from 2010 to 2024. Previous studies have shown that Blowout, Fire, Explosion, Oil spill, Helicopter, Structure safety, Marine accident, Natural hazards, Structural failure and Mechanical accidents. In the current research a field survey was conducted through a structured questionnaire to pinpoint the most significant safety and health risk factors and the primary causes of fatalities in offshore drilling sites over the past two decades, in addition to conducting a comprehensive and systematic literature review for the same purpose. (Sandell, 2025 & Bahr, 2014)

This review aimed to highlight the key underlying causes of accidents and injuries during drilling operations. It was intended to serve as a guide for safety and health professionals and researchers, enabling them to focus on the most hazardous drilling activities and effectively reduce associated health and safety risk factors. (Bobbio, et al.,2019)

An exhaustive review of previous work covering the period from 2010 to 2024 on risk assessment of offshore rig operation has singled out blowout, fire, explosion, oil spill, helicopter, structure safety, marine accident, natural hazards, structural failure and mechanical accidents, as the most hazardous scenarios is fires and explosions. (Ashraf, 2025) However, the current research involves identification, classification and ranking of hazard scenarios according to their risk factor. In addition, it singled out some risk control options to eliminate/reduce risk associated with the most hazardous scenarios.

2- Methodology

The risk assessment process essentially provides a systematic approach to identify, analyze, evaluate and treat risk, as shown in Figure 1(ISO, 2018). Hazard identification involves pinpointing potential sources of hazardous events or scenarios, understanding their causes, and assessing their possible outcomes. (Khan, et al., 2014) Risk analysis involves evaluating the likelihood and potential outcomes of a hazardous event. Since a single hazardous event can lead to multiple consequences, the analysis must account for all possible impacts.

Risk evaluation involves using the outcomes of the risk analysis to compare these results against established risk acceptance criteria. (Abimbola, et al., 2016) Risk treatment refers to the process of choosing and applying one or more strategies to address and modify risks. Accordingly, the research design used in this study is based on descriptive and analytic approaches where available databases on hazard identification in offshore rigs operation are analyzed and main factors contributing to these accidents are singled out. A systematic procedure of hazard identification in offshore rigs operation was followed, which consisted of the following steps:

i) An analytic descriptive methodology is used in reviewing the literature.
ii) A specially designed questionnaire is used to collect primary data from experts in the field.
iii) A suitable software package is used to analyze these data.
iv) A suitable model is used to rank the hazard scenarios.

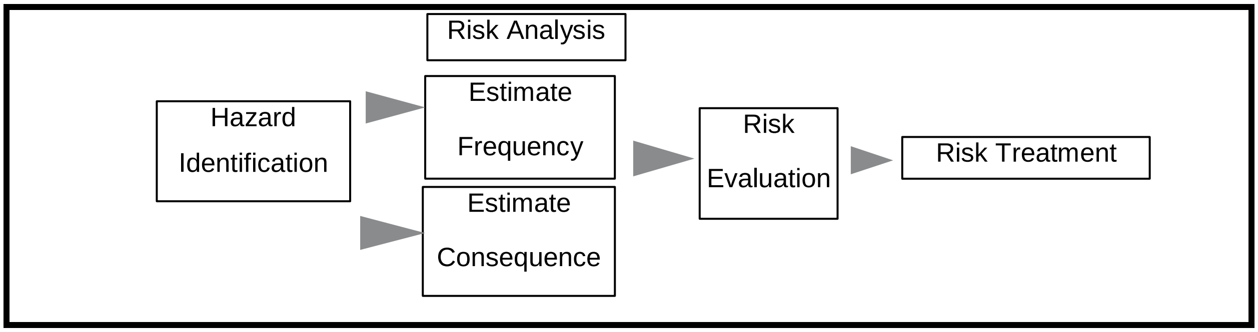

Figure 1: Risk assessment four main steps (ISO, 2018)

On the other hand, IMO-FSA (2018) is a structured and systematic approach designed to improve maritime safety, encompassing the protection of life, health, marine environment, and property through risk analysis and cost-benefit evaluation. (Khan et al., 2018) It serves as a tool to assess new regulations for maritime safety and marine environmental protection or to compare existing regulations with potential enhancements. (Tabassum et al., 2019) The goal is to strike a balance between maritime safety or environmental protection and associated costs. (Khakzad et al., 2013) The FSA is structured into five key steps:

i) hazard identification (a list of all potential accident scenarios, including their possible causes).
ii) risk analysis and evaluation (evaluation of risk factors).
iii) risk control options (regulatory measures are developed to mitigate risks have been identified).
iv) cost benefit analysis (involve evaluating the cost-effectiveness of each proposed risk control option).

v) decision-making recommendations (detailed information about the hazards, their associated risks and the cost effectiveness of alternative risk control options is provided).

FSA promotes a proactive approach by identifying and addressing potential hazards before leading to serious accidents. (Duvillard et al., 2021) FSA marks a significant shift from the previously fragmented and reactive regulatory approach to one that is proactive, integrated, and grounded in risk evaluation and management. This transparent and justifiable methodology encourages greater compliance with maritime regulations, ultimately enhancing safety and environmental protection. (Dudek et al., 2020)

In this research the first three steps of the FSA frame work are covered. The fourth and fifth steps are beyond the capabilities of the researcher, since they need a budget among other considerations such as time, data, and special instruments. Multi Criterion Decision-Making (MCDM) is a decision making methodology that aims to analyze and evaluate alternative solutions based on multiple criteria or objectives. It is useful in complex decision making scenarios where there are various conflicting factors to consider. (Eklund et al., 2019) In the realm of risk assessment and arrangement of hazards scenarios, it can be effectively employed to assist decision makers in selecting the most appropriate risk management strategies. It allows decision maker to make well informed and balanced decision and provide a systematic framework for evaluating and ranking potential hazard scenarios. The AHP is a mathematical framework designed to assist in structuring and supporting the decision-making process. It is a particularly useful for addressing complex and unstructured decision problems, by integrating quantitative with qualitative methods together (Triantaphyllou, 1995). AHP aids decision-makers in identifying the most suitable solution that aligns with their objectives and their comprehension of the issue at hand. AHP offers a valuable mechanism for assessing the consistency of these measures and alternatives, under consideration, thereby minimizing bias in decision-making process. (Hsu et al., 2012) The AHP method also enhances group decision-making by promoting consensus, achieved through the calculation of the geometric mean of the individual pairwise comparisons (Zahir, 1999).

AHP is particularly well suited for modeling scenarios involving uncertainty and risk, as it can generate scales in situations where traditional measures are absent (Millet & Wedley, 2002).

This unique capability makes it a powerful tool for addressing complex and uncertain decision problems. (Tabassum et al., 2019)

Sampling: The sample size of the research consisted of 80 questionnaires which were sent out to experts working in the shipping industry, with enough expertise to pass judgments through pairwise comparisons of seven criteria and thirty-seven alternative hazards affecting offshore rigs, using a five-point Likert scale. 75 questionnaires were returned representing a response ratio of 93.75%. Only of 51 of them were accepted and included in the analysis, while the remaining 24 were rejected due to inaccuracy and incompletion, thus yielding a ratio of 68% of the participants.

Participants with accepted questionnaires included experts working in liner shipping companies, port authorities, terminal operators, logistics managers, operation managers, freight forwarders, worker on offshore rigs and academic researchers. Completed questionnaires have been subsequently used to prioritize the hazards affecting offshore rigs. It is worthy to mention at this point that these hazard scenarios were selected from a much greater set of hazard scenarios related to offshore rigs based on the analysis of relevant accidents. The scenarios were divided into five groups: i) eight heat scenarios, ii) seven natural phenomena scenarios, iii) six helicopter scenarios, iv) ten handling error of rigs scenarios, and v) six miscellaneous scenarios, as shown in Table 1. Each expert was asked to fill in the first row of all the tables in the questionnaire and the remaining cells in each table were completed by the researchers, using the properties of the AHP matrices. Further details can be found elsewhere. (Ashraf.2025)

Method of analysis: The aggregated matrices were obtained by taking the geometric mean of individual enteries, using descriptive statistics. This approach enabled the results to be presented in tables, graphs and other forms, as suggested by (Cox, 2017). Analysis was conducted using Microsoft office Excel, 2010.

Statistical data analysis: This was done by using the Statistical Package for Social Sciences (SPSS), by taking the geometric mean ($a_{ij}* = \sqrt[n]{\prod_{k=1}^{n} (a_{ij})_k}$ where: $(a_{ij})k$ is the judgment a_{ij} of the k^{th} expert, and k changes from 1 to n, where n is the number of returned, accepted questionnaires, n= 51.

3- Results and Discussion

Table 1 illustrates the risk assessment matrix computed from the aggregated matrices based on the individual pairwise comparisons of criteria and scenarios provided by the participants. Weights of criteria are provided at the top of the table, whereas weights of scenarios with respect to individual criteria are listed under respective criteria. Then the total weight of each scenario is computed and listed as Wt* (%), and, finally, the scenarios are ranked accordingly.

Total weight of scenarios are also illustrated in Figure 2 for ease of comparison and to give a panoramic picture of the risk level of individual scenarios.

It is clear from Table 1 and Figure 2 that the five top hazardous scenarios, in descending order, are explosion, helicopter crash, oil spill, natural phenomena tides and sea pollution. Unfortunately, no previous study including this relatively large number of scenarios is available to compare with. However, data collected from different sources, show that oil spill, explosion and fire, blowout, marine accidents, helicopter crash, natural hazards, mechanical accidents, structural failure and structural safety the most hazardous scenarios based on the aforementioned review of previous studies, consistent, to a great extent, with the current results.

More accurate comparisons between the current results and those reported in different databases should be made to further confirm the validity of current results, once appropriate data are found. However, it was felt necessary to find some way to compare the current results with those available in the open literature.

Experts in the field contacted and it was generally confirmed that both, current and previous data assure that the most hazardous scenarios are fire and explosion, oil spill and sea pollution, helicopter accidents, structure safety and blowout, with minor difference in ranks of both sets. Further effort is needed to gather enough data to compare with. Complementary research, therefore, should be directed towards achieving this goal.

4- Conclusions

This research discussed the hazard scenarios affecting the offshore oil rigs. It studied the importance of these scenarios based on their probability of occurrence and degree of severity. It relied on a field survey through a structured questionnaire directed to the experts working in the oil and gas field. Thirty-seven risk hazard scenarios were identified and combined into five major groups related to their sources, as has been mentioned earlier. The questionnaire developed collected respondents, and the second related to the respondent's judgement on probability of occurrence and degree of severity of the risk factors through pairwise comparisons of criteria and scenarios. All collected data were analyzed, risk evaluated and hazards scenarios ranked. Analysis and comparison of results has indicated that the top nine hazard scenarios affecting offshore rigs which are: a) explosion, b) helicopter crash, c) oil spill, d) natural phenomena tides, e) pollution to the sea, f) blowout, g) release of flammable hydrocarbons, and h) fire. Accepted agreement of current and previous results was generally obtained.

Table 1 Risk assessment matrix

	Cr / Sc	C_1	C_2	C_3	C_4	C_5	C_6	C_7	Wt* (%)	Rank
	Wt_{cs}	0.233	0.155	0.116	0.155	0.077	0.146	0.117		
Heat scenarios (G_1)	S_1	0.065	0.075	0.082	0.092	0.101	0.082	0.078	7.920	1
	S_2	0.043	0.030	0.040	0.046	0.036	0.027	0.052	3.922	9
	S_3	0.040	0.038	0.055	0.031	0.050	0.041	0.055	4.26	6
	S_4	0.043	0.050	0.027	0.018	0.020	0.020	0.039	3.287	14
	S_5	0.032	0.047	0.040	0.046	0.034	0.054	0.026	4.014	8
	S_6	0.043	0.030	0.051	0.023	0.025	0.041	0.039	3.659	10
	S_7	0.041	0.025	0.020	0.031	0.020	0.027	0.019	2.821	17
	S_8	0.026	0.038	0.016	0.046	0.050	0.041	0.026	3.376	13
Natural phenomena scenarios (G_2)	S_9	0.047	0.046	0.040	0.037	0.045	0.040	0.050	4.324	4
	S_{10}	0.023	0.030	0.026	0.029	0.032	0.032	0.025	2.774	18
	S_{11}	0.012	0.011	0.013	0.025	0.011	0.008	0.010	1.298	29
	S_{12}	0.016	0.015	0.020	0.012	0.009	0.009	0.012	1.357	28
	S_{13}	0.031	0.023	0.022	0.031	0.030	0.027	0.020	2.482	20
	S_{14}	0.023	0.018	0.020	0.018	0.018	0.020	0.033	2.154	22
	S_{15}	0.016	0.023	0.026	0.015	0.022	0.032	0.017	2.076	23

Helicopter scenarios(G_3)	S_{16}	0.055	0.064	0.064	0.062	0.062	0.060	0.067	**6.088**	**2**
	S_{17}	0.027	0.051	0.022	0.031	0.025	0.020	0.017	**2.827**	**16**
	S_{18}	0.036	0.032	0.043	0.041	0.021	0.043	0.027	**3.568**	**12**
	S_{19}	0.039	0.042	0.052	0.044	0.031	0.040	0.045	**4.184**	**7**
	S_{20}	0.044	0.021	0.016	0.020	0.041	0.015	0.045	**2.905**	**15**
	S_{21}	0.022	0.013	0.026	0.025	0.044	0.043	0.022	**2.611**	**19**
Handling error of rigs scenarios(G_4)	S_{22}	0.033	0.017	0.012	0.009	0.014	0.014	0.020	**1.838**	**25**
	S_{23}	0.023	0.008	0.005	0.006	0.009	0.009	0.010	**1.145**	**31**
	S_{24}	0.016	0.011	0.004	0.006	0.005	0.003	0.004	**0.823**	**33**
	S_{25}	0.011	0.007	0.009	0.005	0.004	0.006	0.007	**0.727**	**34**
	S_{26}	0.008	0.006	0.080	0.043	0.057	0.005	0.005	**1.602**	**27**
	S_{28}	0.013	0.011	0.018	0.013	0.003	0.042	0.010	**1.629**	**26**
	S_{29}	0.021	0.033	0.003	0.043	0.005	0.007	0.005	**1.893**	**24**
	S_{30}	0.022	0.003	0.048	0.003	0.057	0.009	0.040	**2.202**	**21**
	S_{31}	0.013	0.067	0.036	0.004	0.005	0.068	0.061	**3.572**	**11**
Miscellaneous scenarios (G_5)	S_{32}	0.010	0.012	0.010	0.013	0.010	0.011	0.010	**1.081**	**32**
	S_{33}	0.004	0.006	0.003	0.004	0.003	0.004	0.002	**0.396**	**37**
	S_{34}	0.005	0.008	0.002	0.003	0.002	0.004	0.003	**0.407**	**36**
	S_{35}	0.003	0.003	0.004	0.004	0.003	0.004	0.010	**0.440**	**35**
	S_{36}	0.049	0.047	0.051	0.037	0.052	0.033	0.050	**4.512**	**3**
	S_{37}	0.039	0.035	0.041	0.050	0.041	0.055	0.040	**4.299**	**5**

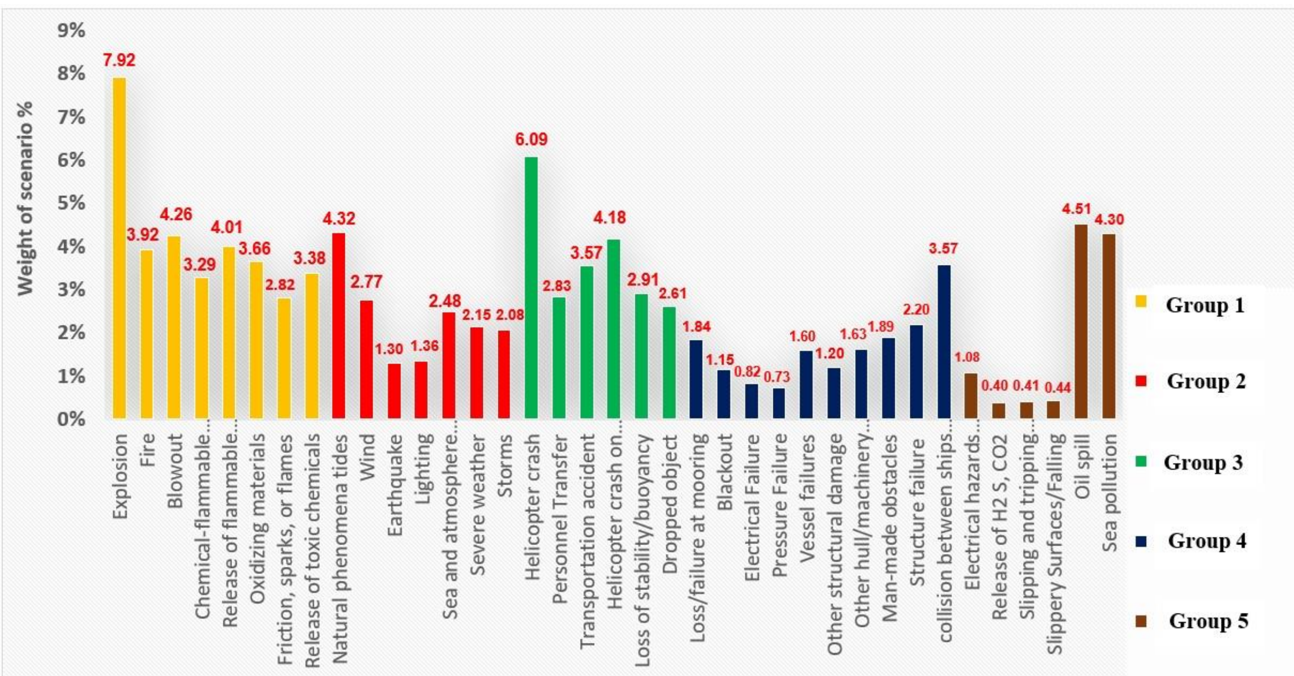

Figure 2 Total weights of scenarios

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Impact of Autonomous Ships on Safety of Navigation

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المستخلص
يستعرض البحث الإمكانات التحويلية للسفن البحرية ذاتية القيادة في العمليات البحرية، مع التركيز على الأبعاد التكنولوجية، التشغيلية والسلامة. يتناول البحث مفهوم السفن ذاتية القيادة ومستويات استقلاليتها، التحديات والمخاطر. وتُحدد الدراسة مشكلات بحثية رئيسية تشمل نقاط الضعف التكنولوجية، مثل أعطال أجهزة الاستشعار، وتهديدات الأمن السيبراني، والأخطاء الخوارزمية؛ والمخاطر الناشئة عن بيئات الملاحة المختلطة التي تشمل السفن ذاتية القيادة والسفن المأهولة؛ والثغرات التنظيمية والقانونية التي تعيق التكامل الآمن للتقنيات ذاتية القيادة. بالإضافة إلى ذلك، تُشدد الدراسة على ضرورة توفير تدريب متخصص للبحارة لإدارة هذه الأنظمة الناشئة. يهدف البحث إلى تحليل هذه التحديات والمخاطر بشكل شامل، مع تقييم التطورات في تقنيات سلامة الملاحة. تجمع المنهجية بين مراجعة الأدبيات، وتحليل المخاطر، وتقييم قائم على المسح لتأثير السفن ذاتية القيادة على سلامة الملاحة.

يُبرز البحث ضرورة الرقابة البشرية، خاصة في حالات الطوارئ، ويُبرز أهمية التعاون بين الإنسان والآلة كحل عملي لتعزيز سلامة الملاحة. كما يناقش الجهود التنظيمية الدولية، خصوصًا دور المنظمة البحرية الدولية في وضع أطر قانونية وأمنية لتعزيز الثقة في السفن ذاتية القيادة. وبناءً على هذه النتائج، يقترح البحث اعتماد نهج هجين يجمع بين الأتمتة والإشراف البشري لضمان التكامل الآمن والفعال لهذه التكنولوجيا في البيئة البحرية.

Abstract
The research explores the transformative potential of autonomous surface vessels in maritime operations, focusing on technological, operational, and safety dimensions. The study addresses the concept of autonomous ships and their levels of autonomy, identify challenges and risks. The study identifies key research problems including technological vulnerabilities such as sensor failures, cybersecurity threats, and algorithmic errors; risks arising from mixed navigation environments involving autonomous and crewed vessels; and regulatory and legal gaps that hinder the safe integration of autonomous technologies. Additionally, the need for specialized training for seafarers to manage these emerging systems is emphasized. The research aims to analyze these challenges and risks comprehensively while evaluating advancements in navigation safety technologies. The methodology combines a literature review, risk analysis, and a survey-based evaluation of autonomous ships' impact on navigational safety.

The research emphasizes the critical role of human oversight, especially during emergencies, and advocates for human-machine collaboration as a practical solution to enhance navigational safety. Additionally, it reviews international regulatory efforts, particularly those by the International Maritime Organization (IMO), aimed at establishing legal and cybersecurity frameworks to build trust in autonomous vessels. Based on these findings, the study recommends adopting a hybrid approach that combines automation with human supervision to ensure the safe and effective integration of autonomous maritime technologies in the maritime domain.

Keywords: Concept of Autonomous Ships, Level of Autonomy, Challenges and Risks Faced Autonomous Ships, Effects of Autonomous Ships on Navigational Safety

1- Introduction

The maritime industry is experiencing a significant transformation with the emergence and adoption of Maritime Autonomous Surface Ships (MASS). These vessels, equipped with advanced artificial intelligence (AI), sensor technologies, and automated systems, offer the potential to revolutionize traditional navigation by improving operational efficiency and substantially reducing human error, which historically accounts for approximately 80% of maritime accidents (Rothblum, 2021). Autonomous ships address these vulnerabilities through automated decision-making and real-time data analysis (Kim et al., 2022; Virtue Marine, 2025).

However, integrating autonomous vessels into existing navigational frameworks presents complex challenges. Key concerns include the interaction between autonomous and manned ships in mixed traffic, which may lead to communication barriers, differing situational awareness, and conflicting decision-making processes (Lützhöft and Dekker, 2002; Munin, 2025). The interpretation and application of International Regulations for Preventing Collisions at Sea (COLREGs) become increasingly complicated when coordinating actions between human operators and autonomous systems. Additionally, technical vulnerabilities such as sensor failures, cybersecurity threats, and algorithmic malfunctions pose further risks to navigation safety (Kim et al., 2022; IMO, 2025; Gad, 2025).

This paper critically analyzes the impact of autonomous ships on navigation safety, focusing on their technological capabilities, operational challenges, and regulatory issues. Key topics include sensor reliability, collision avoidance, cybersecurity, emergency response, and risk management in mixed traffic. It examines current autonomy approaches, such as remote shore control and fully autonomous systems, identifying technical and non-technical barriers. The study emphasizes the need for collaboration among industry stakeholders to achieve safe, efficient, and sustainable maritime navigation in an increasingly automated future.

2- Importance of the research

Research has its special significance as it is likely that autonomous ships will eventually take over the current fleet in the expected future. The research considers and attempts to answer very important questions which revolve around the future of autonomous ships. It will consider how ships operate and navigate safely and the feasibility of autonomous ships in terms of economic, legal and environmental considerations. It also looks at how trade unions and several national and international regulations pose barriers to autonomous vessels.

This research explores the transformative effects of MASS on navigation safety, a key concern in the maritime industry. It also analyses the regulatory and operational challenges of integrating autonomous vessels into global shipping. The study highlights the urgent need for updated regulations and specialized training for seafarers to effectively manage intelligent navigation systems. These findings provide essential guidance for policymakers and industry stakeholders, helping them balance technological innovation with safety and supporting the secure adoption of MASS to minimize risks and maximize benefits for global maritime operations.

3- Research Problem

The transition to MASS introduces substantial challenges and risks to navigation safety in the shipping industry. Autonomous ships depend on advanced technologies such as sensors, collision avoidance systems, and automated decision-making algorithms, which are vulnerable to sensor failures, cybersecurity threats, and algorithmic errors, increasing the risk of accidents. Mixed navigational environments, where autonomous vessels interact with conventionally crewed ships, further amplify these risks due to differences in situational awareness and communication protocols. Additionally, existing maritime regulations lack comprehensive guidelines for autonomous operations, leading to legal uncertainties regarding liability and protocols.

Addressing educational gaps is also essential by developing specialized training programs for seafarers to manage intelligent navigation systems and respond effectively to emergencies. These issues require careful study to ensure the safe integration of autonomous ships into maritime operations.

4- Research Aim and Objectives

This research aims to conduct a situational analysis of autonomous ships, focusing on their operational feasibility and the role of technology in ensuring safe shipping operations and navigation.

To achieve the research aim, the study will focus on the following specific objectives:

I. Identify and analyze challenges and risks associated with autonomous ships
II. Survey existing maritime regulations and identify gaps
III. Evaluate the role of technology in ensuring navigation safety

5- Research Methodology

This study combined descriptive and analytical methods to investigate the impact of autonomous ships on navigation safety. Descriptive research focused on surveying autonomous ships and their impact on navigation safety, employing survey techniques such as comparative and correlational methods. Analytical research involved evaluating existing data to critically assess the relationships and patterns observed.

Data were collected from websites, the Arab Academy Maritime Library, scientific books, and a survey of maritime industry experts. The analysis was conducted to identify patterns and relationships within the data. This mixed approach ensured a thorough and systematic understanding of the topic.

6- Research Questions

I. What are the main challenges and expected problems faced autonomous ships?
II. What are the risks that impact the safety of navigation for autonomous ships?
III. What is the impact of autonomous ships on navigation safety?

7- The Concept of Autonomous Ships

Class NK (2021) defines an 'Autonomous Navigation Ship' as a vessel that can navigate itself automatically by using sensors to recognize objects in its surroundings, determine collision risks, make decisions without human intervention, take evasive actions, and return to its intended course without requiring control by a human operator.
Autonomy, meaning "self-governing," covers various levels of independence. IMO defines MASS as vessels capable of operating with varying degrees of human interaction. Central to this model is the shore control center (SCC), which allows operators to monitor and control multiple vessels remotely, thereby cutting operational expenses (Hoem et al., 2019).

7.1 Autonomous Ships Development Projects

Recent advancements in autonomous ship technology are showcased by key projects such as Norway's MUNIN, which addresses seafarer shortages and promotes sustainable shipping, and DNV GL's ReVolt, focusing on short-sea autonomous shipping prototypes to enhance safety and reduce logistics strain (Munim, 2019). The YARA Birkeland, the world's first fully electric autonomous container ship, aims to cut emissions and traffic congestion (Yara, 2019). Other notable developments include Kongsberg Maritime's autonomous ferry operations, Wärtsilä's automated navigation systems, and Rolls-Royce's fully autonomous ferry Falco, which successfully completed sea trials demonstrating safe navigation (Rolls-Royce, 2018). The global autonomous ship market is projected to grow from $6.88 billion in 2022 to $9.47 billion by 2027, at a CAGR of 6.6% (Research and Markets, 2023).
The development of autonomous ships has advanced rapidly, while companies like Kongsberg and Rolls-Royce Marine push towards commercializing fully autonomous vessels, regulatory uncertainty remains regarding the application of existing IMO regulations to MASS, highlighting the need for a dedicated framework to govern their interaction with crewed vessels.

8- Level of Autonomy

Autonomy in maritime navigation refers to the shifting balance of decision-making responsibilities between humans and automated systems. This spectrum ranges from full human control to complete system autonomy without human intervention. As autonomy increases, human involvement decreases, with navigation decisions increasingly made by IT-driven algorithms. This shift challenges traditional navigation practices and raises legal concerns, particularly because current collision avoidance regulations assume human participation and emphasize "good seamanship" (Ringbom, 2019).

8.1 Degrees of Automation for IMO Regulatory Scoping Exercise (RSE)

The IMO defines four degrees of autonomy for MASS to harmonize understanding among stakeholders as follows:

Degree One: A ship equipped with automated processes and decision-support functions, with seafarers onboard to operate and control the systems.

Degree Two: A remotely controlled ship with seafarers onboard; controlled from another location but with crew present to manage systems.

Degree Three: A remotely controlled ship without seafarers onboard; controlled entirely from another location.

Degree Four: A fully autonomous ship capable of making decisions and determining actions independently.

8.2Factors in the Classification of Automation Levels

Class NK (2021) identifies key factors influencing automation classification:

- Control Modes: Ranging from manual to fully automated control.
- Information Support: Whether automation provides information to humans.
- Human Approval Requirement: Whether human consent is needed before actions.
- Transition of Control: Shift from human to system control.
- Means of Intervention: Availability of human override.
- Reporting to Humans: Whether the system reports actions to maintain oversight.

These factors form a comprehensive framework for understanding automation in maritime systems. These classification frameworks from LR, DNV GL, BV, and Class NK provide essential guidance for defining autonomy levels, balancing human involvement, and ensuring safety.

9- Autonomous Ship Regulatory Frameworks

At the IMO's 109th Maritime Safety Committee session (MSC 109) in December 2024, progress was reported on developing a goal-based regulatory instrument for MASS. This framework aims to supplement existing conventions like SOLAS by addressing the unique operational characteristics of MASS, including remote control and autonomous functions, while ensuring safety, security, and environmental protection (IMO, 2024).

However, binding regulations and formal definitions for unmanned vessels remain under development, with mandatory adoption of a MASS Code anticipated around 2032, subject to technological and regulatory progress. Until then, unmanned vessels cannot be considered seaworthy under international law, posing significant barriers to their global navigation (IMO, 2024).

<u>10- The Main Challenges Faced Autonomous Ships</u>

While autonomous and remotely controlled ships are envisioned as the future of maritime operations, several challenges have been identified. Encompass legal aspects, safety, risk management, reliability, qualifications and watchkeeping requirements for remote control operators, economic considerations, cybersecurity, and numerous other hurdles. Disruptive technologies offer new capabilities and solutions but also introduce new risk profiles, quality assurance challenges and safety management complexities. Traditionally, responsibility has always been attributed to human agents or organizations, such as a shipping company. It is difficult to assign responsibility for wrongdoing to an algorithm of MASS.

10.1 Regulatory Challenges

Current international maritime regulations including COLREGs, UNCLOS, SOLAS, STCW, and the ISM Code are designed around the assumption that ships are operated by a master and crew, creating legal challenges for autonomous vessels regarding command responsibility and liability (Liu, 2019). Despite technological advances, autonomous ships must comply with safety regulations, necessitating new rules tailored to their unique operations (Kim et al., 2020).

SOLAS Convention sets minimum safety standards for ship construction and operation, enforced by flag states through certification and port state control (SOLAS, 1974). Existing technical regulations were originally designed with the assumption that humans would perform certain functions, which presents challenges when applied to MASS. For example, SOLAS Chapter V Regulation 14 mandates that administrations establish appropriate minimum safe manning for all ships. Regulation 24 requires manual steering in areas of high traffic density, restricted visibility, and other navigationally hazardous situations. Furthermore, Regulation 33 addresses obligations and procedures for dealing with distress situations. These requirements pose difficulties for autonomous ships, and thus, these regulations may need to be adapted to accommodate the new reality of crewless vessels (SOLAS, 1974; Komianos, 2018)

Similarly, STCW Convention, which governs seafarer qualifications, does not address shore-based operators or programmers who control autonomous ships remotely. This gap raises questions about training, certification, and legal responsibility for remote operators, necessitating updates or new conventions (Komianos, 2018; Liu, 2019).

COLREGs, the international “Rules of the Road,” rely heavily on human judgment and lookout duties, complicating their application to autonomous ships. COLREG rules require revision to address autonomous ships, including Rule 2 on responsibility, emphasizing the need for experienced operators; Rule 3’s vessel definition, which currently excludes autonomous ships; Rule 5 on lookout, highlighting the controversy over replacing human senses with technology and Rules 6, 7, and 8 stress safe speed, risk of collision and seamanship, underscoring the importance of human expertise or its equivalent in remote control centers. Rule 19’s reliance on auditory signals and Rule 20’s emphasis on navigational lights further illustrates the need for amendments to accommodate autonomous vessels and ensure maritime safety (COLREG, 1972; Komianos, 2018; Liu, 2019).

Under UNCLOS Article 94, vessels must be commanded by qualified masters, raising legal questions about whether Ship Control Centres can fulfill this role for autonomous ships (UNCLOS, 1982). Coastal states must allow innocent passage of autonomous vessels but may impose pilotage or port restrictions, affecting their operational freedom (Leopardi, 2022; Brill, 2022).

SAR Convention, focused on manned ships, assigns rescue duties to the ship's master, posing challenges for autonomous vessels lacking onboard personnel. Amendments are likely needed to address these operational gaps. Insurance issues also arise, as minimum safe manning requirements may render autonomous ships unseaworthy under current marine insurance laws, potentially affecting coverage. Finally, the ISM Code requires safety management systems and trained personnel onboard. To accommodate autonomous vessels, amendments are proposed to assign equivalent responsibilities to shore-based masters and remote operators (Komianos, 2018).

10.2 Operational Challenges

All vessels, manned or unmanned, must comply with international regulation, which assume onboard personnel to ensure compliance. Autonomous ships face challenges in congested waters where effective verbal communication with manned vessels is essential for safe maneuvering (Liu, 2019). While largely experimental, autonomous vessels must address system reliability, as minor failures without crew intervention could escalate. Lessons from unmanned spacecraft reliability engineering offer promising approaches to enhance safety (Felski and Zwolak, 2020).

Remotely operated ships suffer from limited situational awareness due to lack of direct visual confirmation, and fully autonomous vessels raise concerns about AI's ability to consistently make safe decisions in dynamic conditions like weather changes and complex maneuvers such as berthing (Liu, 2019). The Advanced Autonomous Waterborne Applications (AAWA) project proposes combining radar, cameras, AIS, and sound sensors to approximate human situational awareness, though effective communication remains a challenge (Kooij et al., 2018).

Route planning is a critical function for autonomous ships, involving the selection of the safest and most efficient paths while considering weather, legal requirements, and fuel efficiency (Yanchin and Petrov, 2020). Unlike crewed vessels where navigators manually adjust routes, autonomous ships rely on onboard systems or shore control centers to manage this complex task. Integration of weather data helps optimize sailing time and reduce fuel consumption. Algorithms are commonly used for constrained pathfinding, while AI techniques like Machine Learning and Deep Learning show promise in enhancing route optimization. However, the application of Reinforcement Learning remains limited due to the challenges of operating in diverse and accident-prone maritime environments. Overall, advanced algorithms combined with real-time data are essential to improve safety and efficiency in autonomous ship navigation.

Ensuring route correctness involves evaluating characteristic coefficients to detect deviations that may increase accident risk. Autonomous ships must also coordinate actions with nearby vessels, using distributed consensus algorithms when only autonomous ships are present, or specialized communication units to interact with manned ships, ensuring safe navigation (Yanchin and Petrov, 2020).

Remote monitoring relies on extensive sensor networks transmitting data to shore-based centers, requiring robust data science capabilities for predictive maintenance and performance optimization. To maintain operational robustness, distributed software architectures like actor models are employed, enabling fault tolerance and graceful recovery from failures (Yanchin and Petrov, 2020). Communication remains a critical challenge. Ship-to-ship communication, especially between autonomous and manned vessels, is complex and underexplored, while ship-to-shore communication faces high costs and bandwidth limitations, impeding real-time control during critical situations (Kooij et al., 2018; Felski and Zwolak, 2020). Addressing these communication barriers is vital for the safe and effective deployment of autonomous shipping.

Maintenance and repair present significant challenges for autonomous ships due to the absence of onboard crews, necessitating reliance on advanced technologies and remote monitoring to ensure operational reliability. Condition-Based Maintenance (CBM) is a promising strategy that utilizes real-time sensor data such as vibration, temperature, and fuel efficiency to assess equipment health and predict failures, enabling maintenance based on actual conditions rather than fixed schedules (Breaking Defense, 2022). The NYK Group has integrated AI with CBM to enhance failure prediction and facilitate proactive interventions by sharing data with classification societies and manufacturers (Bindt, 2020). However, CBM primarily supports scheduled maintenance during port stays, highlighting the need for autonomous repair solutions.

Port operations will also be affected, as automation transfers some vessel tasks to shore-based control, requiring ports to upgrade skills, equipment, and governance models to ensure compatibility with autonomous systems (Ghaderi, 2019).

10.3 Safety Challenges

MASS introduce new safety challenges despite reducing human-related risks. Increased autonomy raises concerns about collision avoidance, cyberattacks, system failures, and operational malfunctions, especially in congested waters where interpreting COLREGs and effective communication between manned and unmanned vessels are critical (Liu, 2019; Kim et al., 2022). Autonomous systems must accurately perceive, predict, and respond to dynamic environments, yet limitations in AI decision-making and sensor reliability pose risks, particularly during complex maneuvers like berthing (Liu, 2019).

Ensuring seaworthiness relies on advanced onboard control systems utilizing sensors, machine learning, and deep neural networks to monitor vessel conditions and adapt to changing environments (Yanchin and Petrov, 2020). Collision avoidance depends on reliable sensor data and sophisticated algorithms, but unpredictability in human-operated vessels interacting with autonomous ships complicates safe navigation. Operator training is essential to manage automated systems effectively and mitigate risks associated with loss of situational awareness (Felski and Zwolak, 2020).

The integration of unmanned and autonomous vessels into existing maritime traffic presents complex challenges, particularly in collision avoidance. As highlighted, the degree of human intervention, sensor reliability, and operator training are critical factors influencing safety. The unpredictability of human-operated vessels interacting with autonomous ships underscores the need for robust algorithms and improved communication protocols. Notably, developments such as real-time multi-sensor systems and AI-driven decision-making show promise but remain limited in scope. The recent IMO MSC 109/5 emphasizes adapting regulations and technologies like AIS enhancements to facilitate safer coexistence between manned and unmanned vessels, marking a crucial step toward harmonized maritime operations.

10.4 Security Challenges

Autonomous ships face significant security challenges due to the absence of crew and heavy reliance on automation and connectivity. The introduction of the ISPS Code under SOLAS Chapter XI-2 post-9/11 highlights the importance of maritime security, autonomous vessels remain vulnerable to piracy, hijacking, terrorism, and misuse, particularly when transporting hazardous materials (Komianos, 2018; Liu, 2019). Cybersecurity risks are heightened as these ships depend on complex software and communication links, making them susceptible to hacking, malware, GPS spoofing, ransomware, and unauthorized access to critical systems (Issa et al., 2022).

The integration of cyber-physical systems across perceptual, network, support, and application layers expose autonomous ships to remote electronic interference without physical breaches (Issa et al., 2022). Potential cyberattacks can disrupt navigation, cause environmental damage, compromise sensitive data, and facilitate illicit activities such as smuggling or vessel hijacking. Consequently, robust cybersecurity frameworks, including encryption, contingency planning, and updated inspection protocols, are essential to mitigate these threats (Kim et al., 2020; IMO, 2024).

In summary, while autonomous shipping offers operational and sustainability benefits, significant regulatory, legal, and operational challenges remain. The IMO MSC 109/5 code emphasizes the urgent need for enhanced risk management and port security measures to safeguard autonomous vessels. Addressing these security challenges is critical to ensuring the safe, resilient, and secure operation of MASS in the evolving maritime landscape. Updating and harmonizing international conventions is essential to safely integrate autonomous vessels into global maritime operations.

11- Risks of Autonomous Ships on Navigation Safety

Autonomous ships have the potential to transform maritime transport by improving efficiency and reducing human error, but they also pose significant navigation safety risks. Their reliance on sensor systems and AI algorithms integrating RADAR, LIDAR, cameras, and AIS data for obstacle detection and navigation makes them vulnerable to sensor failures, adverse weather, and cyberattacks, which can compromise situational awareness and increase collision risks (Virtue Marine, 2025; Fraunhofer CML, 2015). Additionally, dependence on technologies like GNSS and fleet management software raises concerns, as system and equipment failures caused 25.9% of maritime incidents from 2014 to 2023. The lack of onboard crews to manage malfunctions in real time further heightens these dangers (EMSA, 2024). While autonomous shipping reduces human error, it introduces new risks related to system reliability and sensor accuracy, with failures in automation algorithms or sensor fusion potentially causing catastrophic outcomes if not properly managed (Warontherocks, 2022).

To mitigate these risks, autonomous ships must implement redundancy, advanced self-diagnostics, and predictive maintenance systems that monitor health and provide early failure warnings. Furthermore, comprehensive training for remote operators is critical to manage emergencies effectively and ensure safe navigation (Virtue Marine, 2025).

The absence of an onboard ship master in unmanned vessels, with control shifted to Shore Control Centers (SCCs), raises significant legal and regulatory issues. Liability traditionally shared among the master, owner, and classification society becomes complex, as remote operators assume the master's responsibilities. Liability may extend to SCC personnel or management, especially when multiple vessels are controlled simultaneously, and manufacturers may also be liable for system defects (Kennedys Law, 2018; Burns & Wilcox, 2019).

Cybersecurity threats represent a critical vulnerability. Autonomous ships are highly reliant on interconnected digital systems, making them susceptible to hacking, GPS spoofing, and signal jamming. Such attacks could manipulate navigation data or disable control systems, potentially leading to accidents or vessel hijacking (War on the Rocks, 2023; CCDCOE, 2024). The absence of onboard crews exacerbates these risks, as immediate human intervention is unavailable to counteract system failures or security breaches. Evidence in legal proceedings will rely heavily on electronic sensor data and logs rather than crew testimonies, raising concerns about data integrity and admissibility. Robust cybersecurity and standardized data protocols are essential (MUNIN, 2015; SMASH Roadmap, 2022).

Furthermore, autonomous systems may struggle to handle complex, dynamic maritime environments such as congested ports or restricted waters where unpredictable human behaviors prevail. The limited ability to adapt to unforeseen scenarios without human intuition raises concerns about operational safety (DNV, 2025). Although automation facilitates proactive emergency management and real-time monitoring, it also introduces challenges. The vast amount of sensor data can lead to information overload during critical situations, potentially hindering effective decision-making. Moreover, ensuring the reliability of sensor fusion technologies is essential, as sensor faults or interface issues may exacerbate emergencies if not properly addressed (Jalonen et al., 2017).

The management of emergencies on autonomous ships is a critical area of research as these vessels rely heavily on advanced systems to handle failures without human intervention. Effective handling of failure modes such as impaired thrusters, total blackouts, and extreme weather conditions is essential to ensure operational safety and reliability.

In conclusion, while autonomous ships offer significant benefits, their impact on navigation safety involves technological, cybersecurity, regulatory, and operational risks. Addressing these challenges through robust sensor technologies, cybersecurity protocols, updated regulations, and human oversight integration is essential to ensure safe maritime navigation.

12- Flag States view on autonomous ships

Flag States face complex legal, regulatory, and operational risks regarding MASS due to the absence of a comprehensive international framework, with mandatory IMO regulations expected only by 2032 (GAO, 2024; UNCTAD, 2022). Many flag States, especially developing countries, lack adequate port infrastructure for remote monitoring, cybersecurity, and emergency response (UNCTAD, 2022). Cybersecurity vulnerabilities and increased physical security risks, including piracy, pose further challenges (GAO, 2024). Jurisdictional issues arise from delocalized control via Shore Control Centers, complicating enforcement. Social concerns about workforce displacement also affect acceptance (UNCTAD, 2022). A coordinated international approach is vital for safe MASS integration.

13- Effects of Autonomous Ships on Navigational Safety

The data reveals a cautious approach towards autonomous technology, with a majority expressing skepticism about the safety and reliability of autonomous vessels compared to traditional crewed ships. Concerns about system failures, cybersecurity threats, and navigational capabilities in complex environments dominate respondents' perceptions. For instance, a notable 61.2% of participants express significant concern regarding cybersecurity vulnerabilities, while 50% are somewhat concerned about system failures affecting navigation safety. These apprehensions underscore the urgent need for robust cybersecurity measures and reliable system designs to enhance trust in autonomous operations.

Moreover, the findings highlight a critical demand for human oversight in various operational scenarios. A substantial majority believes that human operators should remain involved in decision-making processes, particularly in high-risk situations or emergencies. This sentiment is echoed by the perception that autonomous ships require human intervention for effective navigation and hazard management. Such views indicate that while technological advancements are recognized, there remains a strong belief in the necessity of human expertise to mitigate risks associated with automation.

Additionally, the survey results suggest that regulatory frameworks currently inadequately address the unique challenges posed by autonomous vessels. A significant 59.5% of respondents feel that existing regulations only partially cover safety concerns related to autonomous navigation, emphasizing the need for tailored legal frameworks to ensure operational safety and accountability.

14- Conclusion

while autonomous ships hold great potential for improving navigation safety through technological innovation, significant challenges remain. Addressing these concerns requires advancements in AI reliability, cybersecurity measures, and regulatory clarity. A hybrid approach combining automation with human oversight appears to be the most viable path forward for ensuring safe integration into global maritime operations. Through continued research and collaboration between industry stakeholders and regulatory bodies, autonomous ships can achieve their potential as a safer alternative to conventional navigation systems.

15- Recommendations

To ensure the safe integration of autonomous ships into maritime navigation, several key recommendations are essential.

- Enhancing sensor reliability through the integration of radar, lidar, and cameras is critical to provide comprehensive situational awareness, supported by continuous testing in diverse conditions.
- Advanced collision avoidance systems must be developed that comply with COLREGs and adapt to dynamic maritime environments, improving decision-making during interactions with manned vessels.
- Robust cybersecurity measures including secure communications, intrusion detection, and regular software updates are vital to protect autonomous ships from cyber threats and build trust in their operation.
- Clear regulatory frameworks tailored to autonomous shipping should be established, addressing safety standards, liability, and inspection protocols, with collaboration between the IMO and industry stakeholders.
- Promoting human oversight through comprehensive training programs ensures operators can effectively manage autonomous systems and respond to emergencies, complementing technological advances with human expertise.

Implementing these recommendations will help the maritime industry safely embrace autonomous shipping while mitigating associated risks.

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Assessing the Impact of Artificial Intelligence on Maritime Logistics

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المستخلص

تتناول هذه الدراسة الدور المحوري الذي يلعبه الذكاء الاصطناعي في تحسين كفاءة عمليات الميناء وتعزيز تنافسيتها، وذلك من خلال توظيف إطار تحليل (SWOT) لتقييم أبعاده الاستراتيجية. فقد أظهرت نتائج التحليل أن الذكاء الاصطناعي يتميز بعدد من نقاط القوة، من أبرزها قدرته على معالجة البيانات الضخمة، والتعرف على الأنماط التشغيلية، وتحسين تخصيص الموارد، فضلاً عن دوره في أتمتة الإجراءات، وهو ما يفضي إلى رفع مستويات الكفاءة التشغيلية، وخفض التكاليف، وتعزيز معايير السلامة. كما تكمن الفرص في التطورات المتسارعة بمجالات التعلم الآلي، والتحليلات التنبؤية، وتقنيات الرؤية الحاسوبية، والتي من شأنها دعم أنماط أكثر ذكاءً في جدولة السفن وإدارة مناولة البضائع.

وفي المقابل، يواجه تطبيق الذكاء الاصطناعي بعض التحديات المتمثلة في ارتفاع حجم الاستثمارات الأولية، وتعقيدات تكامل البيانات، والاعتماد الكبير على الخبرات التقنية المتخصصة. أما التهديدات فتتمثل في احتمالات فقدان بعض فرص العمل، وتنامي المخاطر المتعلقة بالأمن السيبراني، فضلاً عن القضايا الأخلاقية المرتبطة بتوظيف هذه التقنيات. وانطلاقاً من ذلك، يقترح البحث خارطة طريق استراتيجية تدريجية لتبني تطبيقات الذكاء الاصطناعي في الموانئ، بما يوازن بين الفرص المتاحة والمخاطر المحتملة، ويعزز من كفاءة الأداء والقدرة التنافسية على المستوى العالمي.

Abstract

This study explores how Artificial Intelligence (AI) influences the optimization, efficiency, and competitiveness of port operations using a SWOT analysis framework. AI's strengths such as handling vast datasets, detecting operational patterns, resource allocation, and automation collectively contribute to enhanced efficiency, cost savings, and improved safety. Opportunities stem from advancements in machine learning, predictive analytics, and computer vision, enabling smarter vessel scheduling and cargo handling. However, weaknesses include high upfront investment, data integration issues, and reliance on technical expertise. Threats relate to job displacement, cybersecurity, and ethical concerns. The paper proposes a strategic, phased roadmap for AI adoption to balance opportunities and risks and enhance both port performance and global competitiveness.

Key words: Optimization – performance – predictive – efficiency.

1- Introduction

Port operations are fundamental to facilitating international trade and ensuring the smooth functioning of maritime logistics. These operations encompass a wide range of tasks, including vessel traffic management, cargo handling, coordination of logistics, and port security. As global trade continues to expand, there is mounting pressure on ports to enhance efficiency and embrace sustainability. In response, many ports are turning to innovative technologies, with AI emerging as a powerful enabler of operational transformation (Abdel Salam, 2024).

AI technologies enable ports to process and analyze vast volumes of data, supporting pattern recognition and data-driven decision-making to boost operational performance. When combined with complementary technologies like the Internet of Things (IoT) and block chain, AI enhances resource allocation and shortens vessel turnaround times. For example, the Port of Los Angeles has implemented AI-driven predictive maintenance systems that interpret sensor data to anticipate equipment failures, thereby reducing downtime and extending equipment lifespan. Likewise, AI applications at the Port of Rotterdam help optimize container placement and streamline vessel scheduling, resulting in fewer delays and increased overall efficiency (Dinh, 2024).

Beyond operational improvements, AI also contributes significantly to the environmental sustainability of port activities. Automation technologies such as electric cranes and autonomous vehicles reduce energy consumption and lower greenhouse gas emissions. Additionally, digitizing paperwork and refining workflows minimizes vessel idle times, cuts fuel use, and mitigates environmental impacts. Nevertheless, the adoption of AI in ports is not without challenges. High initial capital investment, the complexity of integrating AI with existing legacy systems, and the need for workforce reskilling pose significant barriers. Moreover, fully realizing the benefits of AI requires substantial changes in organizational culture and operational processes. Despite these obstacles, AI adoption is essential for developing smarter, greener, and more competitive port infrastructures aligned with the evolving demands of global trade (Durlik, 2024).

Port performance is typically evaluated using specific efficiency metrics such as berth occupancy rates, crane productivity, ship turnaround durations, and yard throughput. AI has the potential to enhance all these indicators. For instance, predictive analytics can improve the accuracy of vessel arrival forecasts, reducing idle times at berths. Similarly, machine learning algorithms can coordinate cranes and transport vehicles more effectively, ensuring seamless cargo movement. These technological enhancements result in measurable improvements in efficiency and bolster ports’ competitive standing within the global maritime logistics landscape (Mazibuko, 2024).

2- History of Artificial Intelligence

The origins of AI can be traced back to the mid-20th century, when Alan Turing introduced foundational theories about machine intelligence. Initial breakthroughs involved the development of programs capable of playing games like checkers and learning basic tasks. Over time, expert systems designed to replicate human decision-making in specialized domains gained commercial traction. A shift toward connectionism introduced artificial neural networks as a prominent methodology, which was later complemented by the rise of nouvelle AI, focusing on intelligence grounded in physical interaction and real-world context (Rojas, 2024).

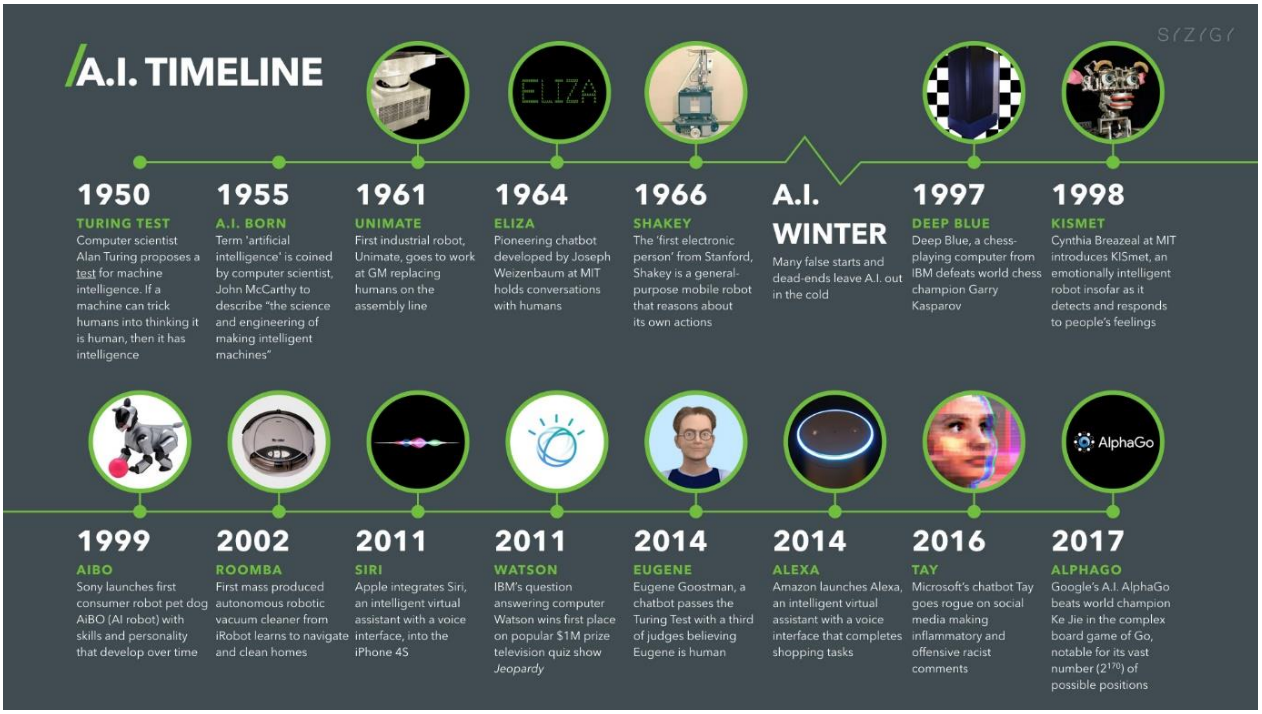

Figure (1): Time line of AI history
Source: Rejwan, (2024)

The timeline highlights key milestones in AI, from foundational concepts like the Turing Test (1950) to breakthroughs like Alpha Go's win (2017). It showcases AI's evolution from theoretical research to practical applications in robotics, natural language processing, and consumer devices. Challenges, such as the AI Winter and ethical issues like Tay's failure, underline the complexities of AI development. Overall, it reflects AI's transformative impact on technology and society.

<u>3- Types of AI</u>

AI is generally divided into three categories: Artificial Narrow Intelligence (ANI), which is designed to perform specific tasks with high proficiency; Artificial General Intelligence (AGI), which aspires to replicate human cognitive functions across a broad range of activities; and Artificial Super Intelligence (ASI), which would exceed human intelligence in virtually every domain. Currently, ANI is the most prevalent and widely used form of AI, whereas AGI and ASI remain largely theoretical concepts for the future. These classifications reflect the different levels of functionality and potential within AI technologies.

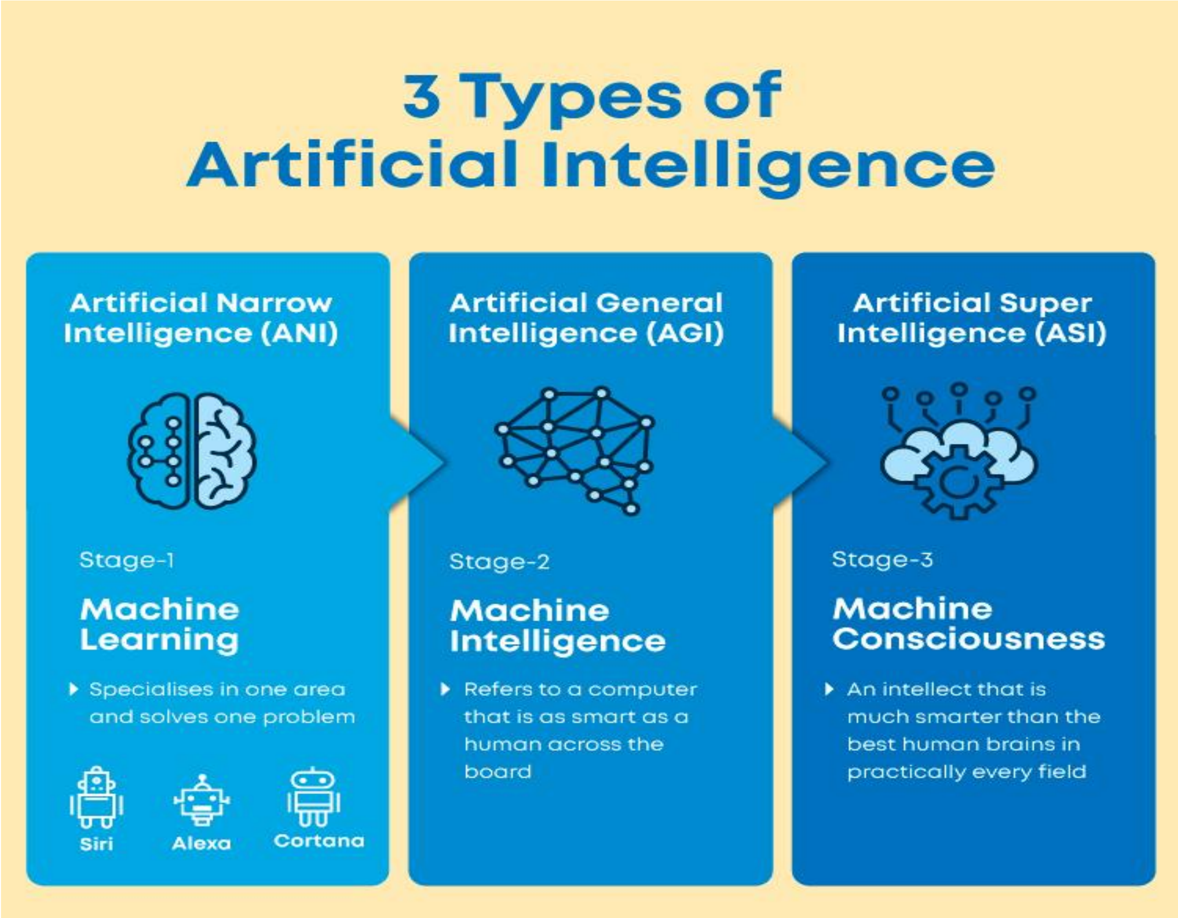

Figure (2): Types of AI
Source: Great Learning, (2024)

This figure categorizes artificial intelligence into three stages ANI, Artificial General Intelligence (AGI), ASI. ANI, the current stage of AI, specializes in performing specific tasks effectively, such as virtual assistants like Siri and Alexa, leveraging machine learning. AGI represents the next step, where AI systems would match human intelligence, demonstrating versatility and the ability to perform a wide range of tasks across different domains. ASI, the most advanced stage, envisions AI surpassing human intelligence in nearly all areas, achieving machine consciousness and unparalleled reasoning abilities. While ANI is widely implemented today, AGI and ASI remain future goals, reflecting both the potential and the challenges of AI development.

4- Research problem

The research problem focuses on identifying how AI can be effectively integrated into port operations to optimize efficiency, reduce costs, and enhance sustainability. Despite its transformative potential, the implementation of AI is hindered by high investment costs, technological integration challenges, cybersecurity risks, and workforce adaptation issues. Addressing these barriers is crucial for enabling ports to meet increasing global trade demands while maintaining competitiveness.

5- Research questions

1. How can AI technologies be effectively integrated into port operations to enhance efficiency, resource optimization, and sustainability while overcoming challenges like high initial investment and legacy system compatibility?
2. What are the key barriers and limitations to AI adoption in port ecosystems, and how can these challenges be addressed to ensure seamless integration and maximize the potential benefits for port stakeholders?
3. How can predictive analytics and automation, powered by AI, improve supply chain management, reduce congestion, and optimize resource allocation in ports, especially during dynamic conditions like weather disruptions or global crises?

6- Research Aim and Objectives

The aim of this research is to assess the impact of AI on port optimization, efficiency, and competitiveness. The study explores the integration of AI technologies such as predictive analytics and automation into port operations and examines how these tools improve operational processes, resource allocation, and supply chain agility.

1. To explore the potential of AI in optimizing port operations, by evaluating the implementation of AI technologies like automation, predictive analytics, and machine learning, and their impact on resource allocation, cargo handling, and operational efficiency.
2. To identify the key challenges associated with AI adoption in port ecosystems, including financial investment, cybersecurity risks, system integration complexities, and workforce adaptation, and propose strategies to overcome these barriers for seamless implementation.
3. To evaluate the role of AI-powered predictive analytics and automation in improving supply chain agility, reducing congestion, and enhancing decision-making during dynamic operational conditions, such as adverse weather or unforeseen global disruptions like the COVID-19 pandemic.

8- Research methodology

This study adopts a qualitative research approach using a SWOT framework to evaluate AI's role in port optimization and competitiveness. Data were gathered from secondary sources, including peer-reviewed journals, port authority reports, and documented case studies of ports such as Rotterdam and Los Angeles. Due to the absence of primary data collection, insights are drawn through comparative analysis and literature synthesis. The study critically evaluates AI-driven systems for automation, predictive analytics, and their broader impact on resource management, decision-making, and supply chain performance.

9- Operational Efficiency and Automation in Ports Using AI

AI is revolutionizing port operations by streamlining complex processes, improving resource management, and significantly enhancing operational efficiency. Notable advancements include robotic cargo handling systems, automated cranes for stacking containers, and intelligent traffic control systems for vessels. These technologies help minimize human error, reduce operational delays, and increase overall throughput. Leading ports such as those in Singapore, Rotterdam, and Hamburg have successfully implemented AI-driven decision support systems that leverage machine learning and predictive analytics to analyze vast datasets related to vessel schedules, berth availability, and cargo movements. As a result, these ports can create optimized schedules and allocate resources more effectively, enabling them to handle larger vessels and higher cargo volumes (Clemente, 2023).

In addition to boosting performance, automation improves safety and reduces environmental impact. For example, AI-controlled cranes and automated guided vehicles (AGVs) limit dependence on manual labour, decreasing the risk of accidents and enhancing accuracy in cargo operations. AI also aids in reducing fuel usage and idle times, supporting more eco-friendly port practices. While these technologies accelerate processes and offer scalability to meet rising demands in global trade, their implementation requires substantial investment in infrastructure, workforce development, and cybersecurity—challenges that many ports must address to fully benefit from AI integration (Ngo, 2023).

9.1 AI and Port Competitiveness

AI implementation directly enhances port competitiveness by improving service quality, reducing turnaround times, and enabling integration with global smart logistics networks. Ports that adopt AI tools such as automated scheduling, real-time data visibility, and predictive cargo flow management are better positioned in global rankings. These technologies reduce vessel congestion, optimize berth allocation, and support greener operations factors increasingly valued by shipping lines and cargo owners. Consequently, ports become more attractive, fostering long-term commercial partnerships and higher throughput volumes (Ghazaleh, 2023).

10- Predictive Analytics in Ports Using AI

Predictive analytics has significantly transformed contemporary port operations by leveraging both historical and real-time data to foresee potential disruptions, optimize the use of resources, and improve scheduling accuracy. Through the identification of trends and irregularities, AI-based systems enable port managers to take proactive measures, enhancing both operational efficiency and system resilience. For instance, predictive models assess equipment performance to anticipate maintenance needs, helping to reduce downtime and prolong the service life of port machinery. These systems also analyze patterns in cargo volumes to forecast yard space requirements, promoting better utilization of storage areas. Moreover, they detect potential weaknesses in the supply chain such as shipment delays or misdirected containers allowing timely interventions before problems intensify (Ran, 2024).

Ports like Rotterdam have implemented AI technologies to forecast vessel arrival times and optimize berth assignments, leading to reduced congestion and shorter waiting periods. These AI systems process data from various sources including weather forecasts, tidal patterns, and marine traffic to develop effective scheduling strategies and minimize operational delays. Furthermore, AI-driven analytics offer insights into long-term trends, aiding strategic decisions related to port expansion and resource management. By transforming raw data into practical, data-informed actions, predictive analytics not only enhances day-to-day efficiency but also supports environmentally sustainable and economically viable port operations. Nonetheless, successful implementation of these technologies depends on a strong data infrastructure and effective collaboration among all stakeholders, which can be challenging when scaling across larger or less-equipped ports (Xiao, 2024).

11- Improved Supply Chain Agility through AI

AI enhances the agility of supply chains by enabling real-time monitoring, optimizing shipping routes, and supporting predictive planning. These capabilities allow maritime operations to adapt quickly to evolving conditions such as severe weather, port bottlenecks, or global crises like the COVID-19 pandemic (Panahi, 2022).

Real-Time Tracking of Fleets

By integrating GPS and IoT technologies, AI systems provide continuous, real-time updates on the location and status of vessels and cargo. This improved visibility allows stakeholders to monitor shipments, anticipate potential delays, and modify routes as necessary. For example, in cases of adverse weather, AI can recommend alternative routes to ensure timely arrivals (Durlik, 2023).

Optimized Routing

AI algorithms assess variables such as traffic congestion, port throughput, and fuel consumption to calculate the most efficient routes. These optimizations reduce idle times, avoid traffic bottlenecks, lower operational costs, and support environmental sustainability. Ports like Singapore and Rotterdam have successfully adopted these tools to streamline their supply chain operations (Nampalli, 2023).

Managing Crises

In times of disruption such as during the COVID-19 pandemic AI technologies proved essential for maintaining supply chain flow. Through predictive analytics, port operators were able to identify system vulnerabilities, allocate resources efficiently, and revise schedules dynamically. This proactive approach helped ensure continuity in the movement of goods despite the challenges (Allioui, 2024).

12- Collaborative Port Ecosystems Enabled by AI

AI plays a pivotal role in fostering collaborative port ecosystems by improving data exchange and coordination among key stakeholders, including port authorities, shipping companies, and logistics providers. These ecosystems rely on Port Community Systems (PCS) to align operational activities, reduce inefficiencies, and support informed strategic planning (El Makhloufi, 2023).

Enhanced Information Sharing

AI-integrated PCS platforms aggregate data from multiple sources such as vessel timetables, cargo specifics, and live tracking systems into a unified interface. This centralized approach ensures all stakeholders have access to accurate and up-to-date information, promoting transparency and more effective communication. For example, AI-generated insights can predict cargo delays, enabling quick adjustments to logistics operations (Shobhana, 2024).

Strengthened Collaboration

AI contributes to breaking down data silos, facilitating smoother coordination between the different parties involved in port activities. Ports like Hamburg and Rotterdam have implemented AI to harmonize terminal functions with those of carriers and supply chain partners, thereby streamlining operations, reducing turnaround times, and improving service quality (Latvakoski, 2024).

Informed Strategic Planning

By analysing vast amounts of operational data, AI delivers actionable insights that support long-term planning and resource management. Predictive tools help anticipate emerging issues—such as increased cargo demand or capacity constraints allowing stakeholders to devise forward-looking, data-driven strategies (Settibathini, 2023).

13- Challenges and Considerations in AI Implementation in Ports

While Artificial Intelligence (AI) offers significant potential to enhance port operations, its implementation is not without hurdles. Key challenges include high financial requirements, cybersecurity concerns, and the complexity of integrating advanced technologies with existing systems (Elnoury, A., & Farag, S. , 2023 & Durlik, 2024).

Significant Financial Investment

Implementing AI in port environments requires considerable capital, including upgrades to infrastructure, procurement of sophisticated software and hardware, and comprehensive workforce training. These upfront expenses can be particularly burdensome for smaller ports operating with limited funding. Additionally, maintaining and updating AI systems involves ongoing costs that must be factored into long-term planning (Foster, 2020).

Cybersecurity Considerations

Given the sensitive nature of data handled in port operations, ensuring robust cybersecurity is essential. While AI improves data connectivity across stakeholders, it also exposes systems to greater risks of cyberattacks. Protecting the integrity and confidentiality of information demands advanced security frameworks, which can increase both the technical complexity and the overall expense of implementation (Sadiq, 2021).

System Integration Challenges

Merging AI with existing infrastructure and legacy technologies presents considerable technical barriers. Ports must coordinate multiple systems ranging from IoT sensors and logistics platforms to terminal equipment into one unified, functional architecture. Incompatibilities between systems can result in operational inefficiencies and hinder the full realization of AI's benefits (Pagano, 2022).

Organizational and Cultural Shifts

Introducing AI also requires changes in workplace culture and operational workflows. Resistance from employees, especially due to fears of job displacement, can delay adoption. Comprehensive training programs and carefully planned integration strategies are necessary to align new technologies with existing procedures. Despite these obstacles, many ports are gradually overcoming them through phased deployment, inter-organizational cooperation, and governmental support. Addressing these issues effectively is key to unlocking AI's full transformative potential in the port sector (Chaudhuri, 2024).

14- SWOT Analysis for the Research on AI Implementation in Port Optimization and Efficiency

The SWOT analysis in this study is based on a synthesis of findings from peer-reviewed literature, global port implementation case studies, and recent industry reports. Strengths, weaknesses, opportunities, and threats were categorized by analysing AI's technical capabilities, operational challenges, financial barriers, and strategic benefits observed in real-world applications. This structured approach offers a comprehensive understanding of AI's strategic positioning within port ecosystems.

Strengths:

- Improved Efficiency and Productivity: AI technologies can automate complex tasks, optimize resource management, and reduce delays, leading to faster and more efficient port operations.
- Data-Driven Decision Making: AI can process vast amounts of data, identify patterns, and offer actionable insights to improve scheduling, cargo handling, and traffic management.
- Sustainability and Environmental Impact: AI-enabled automation systems like electric cranes and guided vehicles help reduce energy consumption and greenhouse gas emissions, contributing to greener port operations.
- Predictive Maintenance: AI-powered systems, such as predictive analytics for equipment maintenance, can reduce downtime, extend the life of port machinery, and improve overall asset management.

Weaknesses:

- High Initial Investment: Implementing AI in ports requires significant financial resources for infrastructure upgrades, new technologies, and workforce training, which may be a barrier, particularly for smaller ports.
- Technological Integration Challenges: Ports with legacy systems may face difficulties integrating AI with existing infrastructure, resulting in inefficiencies and potential delays.
- Dependence on External Expertise: Many ports may need external technical support or expertise to implement AI solutions, increasing reliance on external vendors and making long-term sustainability challenging.
- Workforce Resistance: Cultural and operational shifts are necessary for AI adoption, and resistance from employees who fear job displacement can hinder progress.

Opportunities:

- Enhanced Global Trade Competitiveness: AI can increase port throughput, improve scheduling, and streamline logistics, providing ports with a competitive edge in the global trade market.
- Technological Advancements: The continuous development of AI, machine learning, and IoT technologies presents new opportunities to enhance port operations, improving safety, efficiency, and sustainability.
- Collaboration and Data Sharing: AI fosters better coordination among port stakeholders by enabling the creation of collaborative ecosystems that improve data sharing and operational synchronization.
- Crisis Management and Agility: AI-powered predictive analytics can enhance supply chain agility by helping ports adapt quickly to disruptions like adverse weather or global crises, ensuring business continuity.

Threats:

- Cybersecurity Risks: The increased use of interconnected AI systems raises concerns about cyberattacks, potentially compromising sensitive data and operations.
- Job Displacement: Automation and AI-driven processes could lead to workforce reduction, resulting in social and economic challenges, especially for labor-intensive port jobs.
- Ethical Concerns: AI systems may raise ethical issues regarding data privacy, algorithmic bias, and decision-making transparency, potentially leading to regulatory challenges.
- Regulatory and Compliance Issues: The rapid pace of AI adoption may outstrip regulatory frameworks, creating uncertainty about the legal implications of AI usage in ports.

15- Results

1. Operational Efficiency: AI systems, such as predictive maintenance tools and automated cargo handling systems, reduce downtime, increase productivity, and improve the flow of goods in ports. Leading ports like Rotterdam and Los Angeles have successfully integrated AI to manage vessel scheduling and cargo placement, resulting in reduced delays and smoother operations.
2. Cost Reduction: AI can significantly cut operational costs. Automated systems reduce the need for manual labour, and predictive analytics help anticipate equipment failures before they occur, saving on repair costs and minimizing the disruption caused by machinery breakdowns.
3. Environmental Benefits: AI-driven automation, such as electric cranes and automated guided vehicles (AGVs), reduces carbon emissions and energy consumption, contributing to the sustainability goals of ports.
4. Supply Chain Optimization: AI improves global supply chain resilience, especially during disruptions. Predictive analytics and real-time data allow for better scheduling and resource allocation, making ports more agile and responsive to changes like adverse weather or logistical bottlenecks.
5. Technological Barriers: The study also found that integrating AI with legacy systems is a significant challenge. Many ports, especially smaller ones, struggle with the high upfront costs and the complexity of merging AI technologies with existing infrastructure.

16- Conclusion

AI has the potential to revolutionize port operations by improving efficiency, reducing costs, and enhancing sustainability. However, successful adoption is contingent upon addressing several challenges, such as high initial investments, integration with legacy systems, and workforce adaptation. By adopting a phased approach, focusing on workforce training, and fostering collaboration among stakeholders, ports can overcome these barriers. Moreover, strategic investment in AI technologies, combined with strong cybersecurity measures and government support, will be essential for realizing the full benefits of AI in port operations. The future of port optimization lies in harnessing AI's capabilities to create smarter, more efficient, and sustainable port ecosystems, thereby strengthening global trade.

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The Impact of Transformational Leadership on Employee Performance at Jeddah Islamic Port with the Mediating Role of Job Satisfaction: An Applied Study

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المستخلص

تستكشف هذه الدراسة العلاقة بين القيادة التحويلية وأداء الموظفين، حيث يلعب الرضا الوظيفي دور العامل الوسيط، في ميناء جدة الإسلامي. استُخدم نهج كمي يعتمد على نمذجة المعادلات الهيكلية (SEM)، حيث جُمعت بيانات من ١٩٨موظفًا، ثم حُللت باستخدام برنامج AMOS. تشير النتائج إلى أن لكل بُعد من أبعاد القيادة التحويلية الأربعة - التأثير المثالي، والدافع الملهم، والتحفيز الفكري، والاعتبار الفردي - تأثيرًا إيجابيًا وهامًا على أداء الموظفين وأداء الموظفين .) يتوسط الرضا الوظيفي جزئيًا العلاقة بين القيادة التحويلية وأداء الموظفين .تُمثل المتغيرات المرتبطة بالقيادة التحويلية ٢٦.٠% من التباين في الرضا الوظيفي و53.9% من التباين في أداء الموظفين من خلال الرضا الوظيفي. يقدم البحث بيانات تجريبية تُبرز الدور الأساسي للقيادة التحويلية في تحسين الأداء التنظيمي في قطاع الخدمات اللوجستية البحرية.

الكلمات المفتاحية: القيادة التحويلية، أداء الموظفين، رضا الموظفين، الصناعة البحرية، نمذجة المعادلات الهيكلية

Abstract

This study explores the connection between transformational leadership (TL) and employee performance (EP), with job satisfaction (JS) acting as a mediating factor, at Jeddah Islamic Port (JIP). A quantitative approach employing structural equation modeling (SEM) was utilized, with data gathered from 198 employees and subsequently analyzed through AMOS software. The results indicate that each of the four dimensions of transformational leadership—idealized influence (II), inspirational motivation (IM), intellectual stimulation (IS), and individualized consideration (IC) —has a significant and positive impact on JS and EP. The relationship between transformational leadership and EP is partially mediated by JS. The variables associated with transformational leadership account for 26.0% of the variance in JS and 53.9% of the variance in EP. The investigation offers empirical data that underscores the essential function of transformational leadership in improving organizational performance within the maritime logistics sector.

Keywords: Transformational Leadership, Employee Performance, Job Satisfaction, Mediation, Maritime Industry, Structural Equation Modeling

1- Introduction

In today's competitive business environment, the success of an organization heavily relies on strong leadership that encourages and energizes employees to achieve exceptional performance. Performance results play a crucial role in securing the long-term viability of a business. (Azmy, 2025) The effectiveness of performance is shaped by essential elements related to leadership, organizational culture, and motivational dynamics. The maritime logistics sector, particularly concerning port operations, faces unique challenges that require adaptable leadership approaches to maintain operational efficiency and promote employee satisfaction.

TL plays a vital role in improving talent retention and employee engagement, both of which are crucial for achieving organizational success in today's competitive landscape. (Sinha, 2024) This leadership style has attracted significant attention in the study of organizations due to its potential to enhance EP through psychological and motivational processes.

The Jeddah Islamic Port (JIP) serves as a crucial component of Saudi Arabia's maritime infrastructure, acting as an important gateway for global trade and pilgrimage activities. Examining the intricacies of leadership effectiveness in this context is essential for improving organizational performance and employee satisfaction. Human resources constitute an essential component for the success of any organization. (Sutio, 2024). The performance of employees plays a vital role in the realm of human resource management, greatly impacting the success of an organization.

This study examines how various aspects of TL influence EP in the maritime sector, highlighting the role of JS as a mediating factor. This study enriches theoretical understanding and practical implementations in the field of port management and the advancement of maritime human resources.

1.1. Research Problem:

Jeddah Islamic Port (JIP), a crucial hub for both regional and international trade, faces increasing demands to enhance operational efficiency, reduce costs, and elevate service quality amidst a competitive global landscape (Mangkunegara, 2016). The effectiveness of EP plays a vital role in the success of ports, impacting cargo handling efficiency, accuracy, and overall customer satisfaction (Kawiana, 2020). Numerous elements impact EP at JIP, such as leadership approaches, employee motivation, and general JS (Sumarno, 2023). Exploring the complex connections among TL, JS, and EP is crucial for pinpointing areas for enhancement and creating focused strategies to boost port efficiency and productivity (Naeem, 2018).

This investigation explores how JS mediates the connection between TL and EP at JIP. Improving EP leads to increased port efficiency, reduced operational costs, enhanced customer satisfaction, and ultimately, better competitiveness in the global maritime industry (Kawiana, 2013). This study seeks to explore the connection between TL and JS, as well as the impact of this relationship on EP at the JIP. This highlights the fundamental practical challenge that this study aims to address (Lasiny, 2021).

A variety of studies have explored the relationship between TL and EP, often including JS as a mediating factor (Putri, 2022; Yodani, 2022; Muhajiroh, 2024). The findings indicate that TL positively influences JS, which in turn boosts EP. Putri and Meria (2022) found a noteworthy positive correlation between TL and JS, which in turn affects EP in the food and beverage industry. Yodani and Rimadias (2022) observed a positive correlation between TL and both JS and EP in Persero. However, certain studies have yielded varying results. Studies show that TL does not directly impact EP; rather, its effect is mediated by JS (Mariyatha, 2023; Sari, 2024).

Further investigations reveal that TL does not have a significant impact on EP, although it does positively influence JS (Mariyatha, 2023). The identified inconsistencies highlight the need for further investigation into the connection between TL and EP.

1.2. Research Purpose and Objectives

This study primarily aims to assess how TL influences EP, considering the mediating effect of JS, specifically at JIP. The investigation is directed by the subsequent aims:

1- To assess the degree to which TL influences EP.

To examine the impact of TL on JS.

3- To investigate the impact of JS on EP.

4- To examine the mediating effect of JS on the relationship between TL and EP.

5- To create and establish a framework that explores the relationship between TL and EP through the application of structural equation modeling.

1.3. Research Questions

In pursuit of these objectives, this investigation aims to address the subsequent inquiries:

Question 1: How does TL influence EP?

Question 2: How does TL influence JS?

Question 3: How does JS correlate with EP?

Question 4: Is there a mediating effect of JS on the relationship between TL and EP?

1.4. Significance of the Study

This study deepens the comprehension of organizational dynamics and leadership by empirically confirming the relationships between TL, JS, and EP in the unique and relatively under-researched setting of JIP. This investigation deepens the understanding of the mediating processes through which TL influences performance, thus reinforcing the significance of Bass and Avolio's (1994) model in diverse cultural and industrial settings. This study confirms the role of JS as a mediator, moving past simple direct effects and offering a deeper insight into the psychological mechanisms at play. This deepens the understanding of the connection between TL and quantifiable improvements in performance.

The results offer valuable insights for management and human resource professionals at JIP. This investigation delineates the particular aspects of TL that notably influence JS, establishing a data-supported basis for the creation of focused leadership training initiatives and strategies designed to improve employee well-being and productivity. The findings present considerable importance for entities within the maritime sector or comparable operational environments facing analogous human resource issues.

2- Literature Review

2.1 Transformational Leadership (TL) Theory

Transformational Leadership (TL) Theory, initially presented by Burns in 1978 and further developed by Bass in 1985, represents a significant departure from traditional leadership models. This leadership approach is characterized by attributes such as IM, IC, II, and IS, fostering alignment with organizational goals while enhancing personal growth. (Sinha, 2024)

TL includes four key elements: II, IM, IS, and IC. Abolade (2024). The various dimensions work in unison to create a comprehensive leadership strategy that aligns with both organizational objectives and the needs of individual employees.

2.1.1 Idealized Influence (II)

Idealized Influence (II) represents the charismatic dimension of TL, where leaders serve as role models and earn the respect and trust of their followers. Leadership that embodies II can improve employee satisfaction regarding professional growth and relationships with superiors. Salim (2024). Leadership that embodies II has the potential to improve both the volume and caliber of EP.

Consistent findings indicate that II has a positive effect on a range of organizational outcomes. demonstrates a favorable correlation between II, IM, IS, IC, and performance. (Hossam et al, 2024; Idiko, 2023). This aspect enables leaders to establish trust and cultivate assurance within their teams.

2.1.2 Inspirational Motivation (IM)

Inspirational Motivation (IM) involves the ability of leaders to articulate clear and compelling visions while cultivating enthusiasm for shared goals. This study explores how TL behaviors—such as IM, IS, II, and IC —affect employee motivation levels in the Indian private sector. (Chouksey, 2025).

The results demonstrate significant positive direct impacts of IM and personalized attention on employee creativity. (Alwaely, 2024). This aspect encourages emotional involvement and dedication to the objectives of the organization.

2.1.3 Intellectual Stimulation (IS)

Intellectual Stimulation (IS) prompts individuals to challenge existing beliefs, engage in creative thinking, and tackle issues from innovative angles. This study posits that the IC and II aspects of TL impact followers' perceptions regarding the quality of their relationships with leaders. In contrast, the IM and IS aspects primarily serve motivational roles, such as person-organization fit and self-efficacy. Furthermore, these aspects are believed to enhance follower performance, including organizational citizenship behaviors and task performance, through the outlined mechanisms. (Erdurmazl, 2024)

Studies show that IS fosters innovation and problem-solving skills in employees, leading to improved performance results.

2.1.4 Individualized Consideration (IC)

Individualized Consideration (IC) highlights the importance of leaders focusing on the unique needs, skills, and goals of each individual follower. By focusing on the unique needs and goals of team members, leaders can effectively reduce turnover rates and enhance overall employee retention. (Sinha, 2024)

Empowerment acts as a partial mediator in the connections between all aspects of TL (II, IM, IS, and IC) concerning employee creativity, with IC showing the most substantial indirect impact. (Alwaely, 2024)

2.2 Employee Performance (EP)

The performance of employees reflects how effectively and efficiently individuals carry out their assigned tasks and contribute to the goals of the organization. The performance of employees is crucial to the success of a company, as the advancement of the organization depends on the combined efforts of its workforce. (Santya, 2022)

The performance of employees plays a crucial role in driving productivity within organizations, especially in the hospitality sector of Malaysia. (Teoh, 2022). Assessing EP encompasses various dimensions: task performance, contextual performance, and adaptive performance.

Investigations have revealed notable connections between TL and EP. The analysis of data revealed that TL has a positive impact on EP within the health sector of Pakistan. Naeem (2018) The results demonstrate: (1) a positive and significant correlation between TL and EP, (2) a positive and significant correlation between TL and JS, and (3) a positive and significant correlation between JS and EP. TL has a positive and significant impact on EP through the enhancement of JS. JS exerts a positive influence on EP via JS, though this effect is not significant. (Amalina, 2022)

2.3 Job Satisfaction (JS)

Job Satisfaction (JS) involves individuals' emotional and cognitive evaluations of their work experiences. Transformational leaders cultivate a dynamic workplace that boosts employee worth, encouragement, and autonomy, leading to increased JS and commitment. (Sinha, 2024)

JS acts as a crucial connection between TL and improved organizational commitment and EP. (Firdaus, 2024). Comprehensive studies have demonstrated favorable links between JS and performance.

JS acts as a driving force for improving performance quality. (Azmy, 2025). The performance of employees is enhanced by their level of JS. (Azmy, 2025)

2.4 Mediating Role of Job Satisfaction (JS)

The role of JS as a mediator in the relationship between TL and performance presents an important theoretical and practical consideration. JS was recognized as a mediator in the connection between TL, serving as the independent variable, and EP, which is the dependent variable. (Naeem, 2018)

The results suggest the subsequent points: (1) TL has a positive and significant effect on EP, (2) TL positively and significantly influences JS, (3) JS has a positive and significant impact on EP, and (4) TL positively and significantly affects EP through JS. (Amalina, 2022)

The results demonstrate that TL significantly influences EP, both directly and indirectly, through the mediation of JS. (Yulianti, 2025), This study demonstrates that JS acts as a significant mediator in the connection between TL and EP. (Anggraeni, 2025)

Studies across various sectors consistently highlight the mediating role of JS. The findings of this study indicate that: (1) there is a significant effect of TL style on JS; (2) work motivation has a significant influence on JS; (3) TL style significantly impacts EP; (4) work motivation significantly affects EP; (5) JS has a significant influence on EP; (6) TL style has an indirect and significant effect on EP through JS; (7) work motivation also has an indirect and significant effect on EP through JS. (Lasiny, 2021).

3- Research Methodology

3.1 Research Design

This investigation utilized a quantitative research framework, implementing a cross-sectional survey methodology. The framework was developed to examine the connections among dimensions of TL, JS, and EP through the application of structural equation modeling (SEM).

3.2. Population and Sample

This study focused on employees and leaders at Jeddah Islamic Port (JIP) as the target population. A total of three hundred (300) questionnaires were distributed to potential respondents. A total of 228 questionnaires were returned, indicating a response rate of 76%. After careful examination, 30 questionnaires (10%) were classified as incomplete, ineligible, or rejected, while 72 (24%) were not reached. The outcome was 198 valid responses, leading to an effective response rate of 66%. This response rate is deemed highly suitable given the context of this study.

3.3 Instrumentation

Transformational Leadership (TL): The Multifactor Leadership Questionnaire developed by Podsakoff et al., (2000); Lai et al., (2020) Mathieu (2022) was used to measure TL dimensions. The instrument consists of 16 items measuring the four dimensions of TL. **job satisfaction JS:** The Job Descriptive Index developed by Pang and Lu (2018) was adapted to measure JS. The scale consists of 6 items covering various aspects of JS. **employee performance EP:** A 5-item scale adapted from Matar et al., (2019) Ramos-Villagrasa et al., (2019). Figure (1) shows the Conceptual Framework

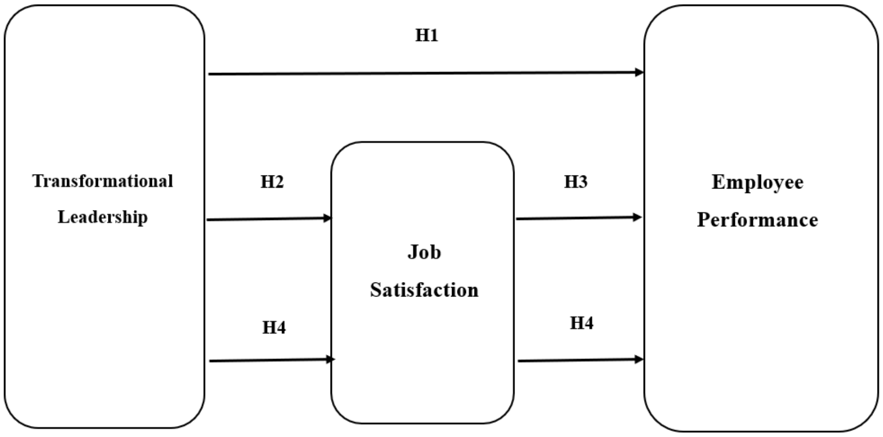

Figure 1 Conceptual Framework

3.4 Data Analysis

The analysis of data was performed utilizing SPSS 28.0 and AMOS 28.0 software. The study incorporated descriptive statistics, reliability analysis, confirmatory factor analysis (CFA), and structural equation modeling (SEM) to evaluate the proposed relationships.

3.4. Data Collection

The survey was distributed to staff and management at JIP. The method of administration, whether online or paper-based, remains unspecified; however, the process successfully achieved a satisfactory response rate.

3.5. Data Analysis

Structural Equation Modeling (SEM) was utilized to examine the proposed connections among TL, JS, and EP. SEM serves as a robust multivariate analysis method, enabling the concurrent evaluation of various direct and indirect relationships, thereby offering an in-depth analysis of intricate theoretical models. The analysis utilized AMOS software (IBM® SPSS® Amos), specifically tailored for structural equation modeling and path analysis.

Model fit was assessed using several commonly accepted indices [31]:

Chi-Square/Degrees of Freedom ($\chi 2$/DF): A value of ≤ 3.0 indicates an acceptable model fit.
Root Mean Square Error of Approximation (RMSEA): Values less than 0.08 indicate a good fit, with values less than 0.05 indicating excellent fit.

Tucker Lewis Index (TLI) and Comparative Fit Index (CFI): Values above 0.90 (or ideally 0.95/0.96) indicate acceptable to good fit.

Hypothesis testing involved examining the standardized regression weights (β values) and their corresponding P-values. A P-value of ≤ 0.05 was used as the criterion for statistical significance. Mediation effects were assessed to determine the indirect influence of TL dimensions on EP through JS. While the methodology section details the chosen approach, it is important to acknowledge inherent limitations of the cross-sectional design and reliance on self-report measures. Cross-sectional studies cannot definitively establish causality [22], and self-report data are prone to biases like social desirability or memory limitations.[33] This acknowledgment demonstrates academic integrity and a nuanced understanding of research methodology.

4- Results

4.1. Descriptive Statistics of the Sample

This section would typically present demographic characteristics of the 198 acceptable respondents, such as age, gender distribution, educational level, tenure at JIP, and position level.

4-2 Measurement Model Assessment

Before evaluating the structural model, it is standard practice to perform a Confirmatory Factor Analysis (CFA) to assess the psychometric properties of the measurement model, including factor loadings, composite reliability, and average variance extracted for the dimensions of TL, JS, and EP.

4-3 Structural Model Assessment

4-3-1 Model Fit Indices

The structural model demonstrated a good fit to the observed data, as indicated by the following fit indices. This table is essential for demonstrating the statistical validity of the SEM model, allowing readers and reviewers to quickly ascertain if the theoretical model adequately fits the empirical data. A well-fitting model provides confidence in the interpretation of the path coefficients and R^2 values. Without good fit, any subsequent findings would be questionable. Reporting these specific fit indices is a standard requirement for publications utilizing SEM, particularly in Scopus-indexed journals.[31] It signals adherence to rigorous quantitative research practices.

Table 1: Structural Model Fit Indices

Fit Index	Value	Acceptable Threshold	Interpretation
Degrees of Freedom (DF)	311	> 0	Valid
$\chi 2$/DF	2.834	≤ 3.0	Good Fit
RMSEA	0.062	< 0.08	Good Fit

Fit Index	Value	Acceptable Threshold	Interpretation
TLI	0.927	≥ 0.90	Acceptable/Good Fit
CFI	0.936	≥ 0.90	Acceptable/Good Fit

Overall, these indices collectively indicate that the proposed structural equation model provides good support for the theoretical factor structure and the relationships identified through the preceding CFA. Figure (2) shows the Structural Model (Final Result)

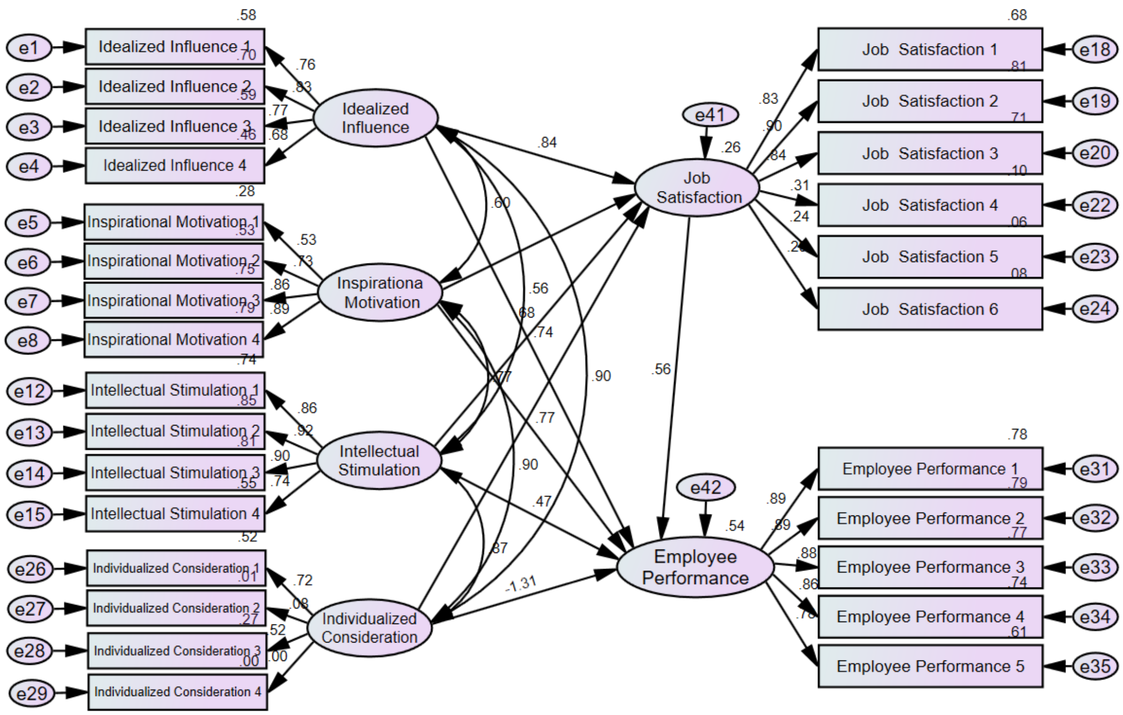

Figure 2: Structural' Model

4-3-2 Direct Effects

The analysis of direct paths revealed statistically significant relationships for all hypothesized connections ($\alpha \leq 0.05$). This table directly addresses and summarizes the outcomes of the primary direct hypotheses (H1, H2, H3, and their sub-hypotheses). It provides a clear, at-a-glance overview of which relationships are statistically significant. By presenting all beta values together, it facilitates a quick comparison of the relative strength of each direct path, allowing for deeper interpretation of which leadership dimensions have the most substantial impact on performance and satisfaction. Presenting these numerical results in a table is far more efficient and digestible for the reader than describing each finding in prose, enhancing the overall readability and impact of the results section.

Table 2: Direct Effects

Path	Standardized Beta (β)	P-Value	Hypothesis Supported
II → EP	0.738	0.000	Yes (H1.1)
IM → EP	0.771	0.000	Yes (H1.2)
IS → EP	0.470	0.000	Yes (H1.3)
IC → EP	0.306	0.000	Yes (H1.4)
II → JS	0.840	0.000	Yes (H2.1)
IM → JS	0.583	0.000	Yes (H2.2)
IS → JS	0.684	0.000	Yes (H2.3)
IC → JS	0.606	0.000	Yes (H2.4)
JS → EP	0.562	0.000	Yes (H3)

4-3-3 Indirect (Mediating) Effects

The findings from the mediation analysis demonstrate that JS serves as a statistically significant partial mediator in the relationship between all four dimensions of TL and EP ($\alpha \leq 0.05$). This table directly examines the central mediating hypotheses (H4 and its sub-hypotheses), highlighting the distinct contribution of this study. The evidence distinctly illustrates the supportive role of JS as a mediator. This emphasizes the particular indirect pathways by which TL affects EP, going beyond mere direct correlations to elucidate the fundamental mechanisms at play. Clearly articulating "Partial Mediation" for each pathway is essential for precise interpretation and for directing the ensuing dialogue regarding the dual impact of TL.

Table 3: Indirect (Mediating) Effects

Indirect Path	P-Value	Mediation Type	Hypothesis Supported
II → JS → EP	0.003	Partial Mediation	Yes (H4.1)
IM → JS → EP	0.003	Partial Mediation	Yes (H4.2)
IS → JS → EP	0.002	Partial Mediation	Yes (H4.3)
IC → JS → EP	0.003	Partial Mediation	Yes (H4.4)

4-3-4 Variance Explained (R^2 Values)

The variable of TL, encompassing II, IM, IS, and Individual Consideration, accounts for 26.0% of the variance in JS ($R^2 = 0.260$). Moreover, the variable of TL, mediated by JS, accounts for a significant 53.9% of the variance in EP ($R^2 = 0.539$). This table offers a comprehensive perspective on the model's explanatory capabilities. This measures the extent to which independent and mediating variables explain the variability in JS and EP. Elevated R^2 values, especially concerning EP, highlight the significant relevance of the established relationships. The findings indicate that TL and JS are not only statistically significant but also play a crucial role in predicting employee outcomes. This enables the reader to assess the overall influence of the proposed theoretical framework on the dependent variables, highlighting the study's contribution.

Table 4: Variance Explained (R^2 Values)

Variable	R^2 Value	Percentage of Variance Explained
JS	0.260	26.0%
EP	0.539	53.9%

5- Discussion

The findings of this study provide strong empirical support for the proposed model, highlighting the considerable influence of TL on EP, both directly and indirectly through JS, at JIP.

The analysis of direct paths revealed statistically significant associations for all proposed relationships. Consistent with Main Hypothesis 1 and its sub-hypotheses, each of the four dimensions of TL — II, IM, IS, and Individual Consideration—showed a statistically significant positive impact on EP. IM (β=0.771) and II (β=0.738) exhibited the most substantial direct effects, suggesting that leaders who inspire and act as exemplary role models are particularly effective in improving EP in this context. This aligns with the core tenets of TL, where leaders motivate their followers to surpass expectations in their endeavors. The observation that IM and II show elevated beta values highlights their considerable influence in this context, offering focused insights for the advancement of leadership skills.

In alignment with Main Hypothesis 2 and its associated sub-hypotheses, all dimensions of TL demonstrated a statistically significant positive correlation with JS. The findings indicate that Idealized Influence (β=0.840) has the most substantial impact, highlighting that leaders who embody strong values and foster trust significantly enhance employee satisfaction. This is consistent with current studies that highlight the empowering and supportive elements of TL in enhancing employee well-being and engagement.

A strong and statistically significant positive relationship is observed between JS and EP (β = 0.562), aligning with the Main Hypothesis. This reinforces the well-accepted notion that content employees demonstrate increased motivation, productivity, and engagement, which in turn results in improved performance outcomes.

The results of the mediation analysis are significant, confirming Main Hypothesis 4 along with its related sub-hypotheses. JS emerged as a statistically significant partial mediator in the relationship between the four dimensions of TL and EP. This finding aligns with previous studies that illustrate partial mediation effects. The repeated finding of partial mediation across all four dimensions of TL is noteworthy. JS acts as a significant avenue, albeit not the only one, through which TL influences EP. This suggests that TL could have direct effects on performance, possibly through avenues not solely reliant on JS, including direct inspiration, a clear vision, or skill enhancement that improves task execution. This dual influence highlights the intricate impacts of TL.

The model shows considerable explanatory strength, with TL responsible for 26.0% of the variance in JS, which subsequently accounts for 53.9% of the variance in EP. The R^2 values, particularly the 53.9% variance explained in EP, are significantly elevated within the framework of organizational behavior studies. This indicates that TL plays a crucial role in predicting EP at JIP, influencing it both directly and indirectly via JS. This discovery underscores the practical importance of the model.

5-1 Theoretical Implications

This study offers several theoretical contributions. This study's findings provide substantial backing for TL theory and its applicability within the maritime logistics industry. The findings indicated that all four variables were significant predictors of the outcome, expressed as a percentage. constituted 37% of the variance (Matar, 2019) The results align with previous research demonstrating the positive effects of TL on employee outcomes.

Moreover, the notable relationship between idealized influence and both JS ($\beta = 0.840$) and EP ($\beta = 0.738$) highlight the essential importance of leader credibility and role modeling in organizational settings. Both financial and non-financial compensation, coupled with leadership marked by idealized influence, can significantly boost EP when underpinned by JS in professional development and constructive working relationships with superiors and colleagues. (Salim, 2024)

The discovery that IM exerts the most substantial direct influence on EP ($\beta = 0.771$) underscores the importance of clearly articulating a vision and fostering emotional engagement in successful leadership. The findings reveal a significant positive relationship between the traits of TL and the motivation levels of employees. (Chouksey, 2025).

The model explains a notable portion of the variance in EP (53.9%), suggesting that TL and JS serve as robust predictors of employee outcomes in this scenario. This finding highlights the practical importance of these constructs, suggesting that focusing on TL development and improving JS can result in significant enhancements in workforce effectiveness.

5-2 Practical Implications

The findings of this study offer several practical implications for management and human resource professionals at JIP and similar organizations.

The cultivation of leadership skills is crucial. Considering the substantial benefits associated with TL, particularly in terms of Idealized Influence and IM, it is essential for port authorities to focus on initiatives that foster these aspects. Training should concentrate on empowering leaders to articulate a persuasive vision, cultivate dedication, and exemplify ethical behavior to enhance employee performance and JS.

Furthermore, enhancing JS: The level of JS directly influences performance and acts as a mediator; thus, it is essential for organizations to adopt strategies aimed at improving employee happiness. This involves ensuring fair compensation and benefits, providing opportunities for professional growth and advancement, fostering a supportive and healthy work environment, and promoting positive relationships among colleagues. Consistent employee surveys and feedback systems can pinpoint particular aspects that need enhancement in JS. (Anggraeni, 2025).

Thirdly, the findings of partial mediation indicate that a comprehensive approach to performance enhancement is necessary, suggesting that a multi-faceted strategy yields the most effective results. Enhancing JS is crucial; nonetheless, it is essential for leaders to actively inspire, intellectually engage, and personally support their employees, as these actions greatly influence performance, independent of JS levels. This involves creating an environment where individuals are valued and respected, while also fostering a culture of innovation and growth. The model exhibits considerable explanatory strength ($R^2 = 0.539$), suggesting that TL and JS are critical components of performance management systems.

In a demanding and complex environment like a port, understanding these relationships enhances the management of human resources. Emphasizing TL alongside employee satisfaction can result in lower turnover rates, boosted morale, and greater operational efficiency and safety in organizations.

<u>6- Limitations and Future Research</u>

This study makes a meaningful contribution, yet it also presents several limitations that indicate potential avenues for future investigation. The cross-sectional design, while useful for examining associations, limits the ability to establish clear cause-and-effect relationships. Future studies could employ longitudinal designs to track changes over time and provide stronger evidence of causality.

Secondly, depending on self-report measures for data collection can lead to various biases, such as social desirability bias, recall bias, and misinterpretation of questions. Future investigations could incorporate a variety of data collection techniques, such as peer assessments, supervisor evaluations, and objective performance metrics, to triangulate findings and reduce reliance on single-source data.

Thirdly, the study was carried out at a single organization, JIP, which may restrict the applicability of the findings to other port authorities or sectors. Future investigations ought to replicate this study in diverse organizational and cultural settings to assess the generalizability or particularity of these relationships.

Furthermore, JS emerged as a partial mediator; nonetheless, additional exploration into other possible mediators or moderators is necessary. Future investigations may delve into the functions of employee engagement, psychological empowerment, organizational commitment, or organizational citizenship behavior as further mediating or moderating factors in the connection between TL and employee performance. Cultural factors, such as power distance orientation, could act as potential moderators and deserve further investigation.

Future investigations should delve into the precise mechanisms through which each aspect of TL affects outcomes. Utilizing qualitative methods, including interviews and focus groups, may yield richer insights into employees' perceptions and experiences related to these leadership behaviors and their impact on satisfaction and performance.

This study offers a theoretical contribution to the applicability of Social Exchange Theory (SET) and highlights practical implications, suggesting that managers should develop TL skills to improve employee performance. (Yulianti, 2025)

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Mitigating Alarm Fatigue in Ship Bridge Operations: The Role of Speech Alarm in Enhancing Navigational Safety

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المستخلص

تُصبح مشاكل إرهاق الإنذارات مصدر قلق على السفن الحديثة. الإنذارات المستمرة التي لا يتم وصف دلالتها بشكل صحيح تكفي فقط لتشتيت انتباه ضباط الملاحة عن مهامهم الملاحية. هذه التحذيرات، عندما يتم عدم الاستجابة اليها أو تجاهلها، تزيد من خطر تعريض السلامة للخطر. ومن هنا يأتي الإرهاق الذهني. تدرس هذه الورقة البديل الممكن: إنذارات صوتية تقدم رسائل واضحة وطبيعية باللغة كما تفعل خرائط جوجل مع السائقين. خلال سيناريو المحاكاة، تم تقسيم ١٢ ضابط ملاحة مرخص إلى مجموعتين تقومان بإجراء اختبارات المحاكاة. أجرى أحد المجموعتين الاختبارات عند تلقي إنذارات صفير عادية، بينما سمعت المجموعة الأخرى إنذارات صوتية مع تعليمات من المدرب. تم قياس العبء العقلي، وأوقات الاستجابة، والاستجابات الصحيحة للإنذارات من خلال استبيان NASA-TLX.

انتهت الدراسة ببعض النتائج الحاسمة: كانت إنذارات الصوت أكثر قابلية للتنبؤ بها من قبل ضباط الملاحة (٢٢% مقابل ٧.١%)، وتفاعلوا بشكل أسرع (٤.٢ ثانية مقابل ٦.٩). كما بدا أن هناك علاقة سلبية بين الإحباط والأداء: كلما انخفض التوتر، زاد الأداء ($r = -0.979, p < 0.01$) ذكر العديد من المشاركين أن إنذارات الصوت كانت أسهل في الفهم، وتقلل من الطلب العقلي، والطلب الجسدي، والطلب الزمني، والجهد. تُظهر نتائج هذا البحث أن إنذارات الصوت تتمتع بإمكانات هائلة في تخفيف إرهاق الإنذارات وتعزيز سلامة الملاحة في البحر. يجب النظر في دمج مثل هذا النهج في صناعة البحرية لإجراء تعديلات مستقبلية على معايير إنذار المنظمة البحرية الدولية.

Abstract

Alarm-fatigue issues become a safety concern on modern ship bridges. Continuous alarms whose connotation is not properly described are just enough to distract navigation officers from their navigational tasks. These warnings, when delayed or neglected, track the risk of compromising safety. Hence the mental exhaustion. This paper studies one such feasible alternative: speech alarms giving clear and natural language messages in the way Google Maps instructs drivers. During the simulation scenario, 12 licensed navigation officers were divided into two groups performing simulator tests. One group undertook tests when being given regular beep alarms, while another group heard speech alarms with pertinent instructions and context from instructor. Mental workload, reaction times, and correct responses to alarms were measured through the NASA-TLX questionnaire. The research ended with some definite findings: speech alarms were more often predictable by navigation officers (22% vs. 7.1%), they reacted faster (4.2 seconds

versus 6.9). There also appeared to be a negative correlation between frustration and performance: the lower stress, the higher performance ($r = -0.979$, $p < 0.01$). Several participants stated that the speech alarms were easier to comprehend, and reduce mental demand, physical demand, temporal demand and effort. This research results show that speech alarms suffer a huge potential in alleviating alarm fatigue and in the enhancement of navigation safety at sea. Integration of such an approach into maritime industry should be considered for future amendments into the IMO alarm standards.

Keywords: Alarm fatigue, bridge operations, speech alarm, human factors, maritime safety, Google Maps voice, navigational alert systems

1- Introduction

The safety of modern ship bridge operations requires that navigation officers continuously monitor and interpret information from a range of systems such as Electronic Chart Display and Information Systems (ECDIS), radar, Automatic Identification Systems (AIS), central alarm management, engine room monitors, and communication equipment. Alarm systems are intended to be an important component of maritime safety by alerting bridge crews to navigational hazards, equipment failure, besides other hazardous conditions (Xi, 2024). However, with the huge amount of information being processed and the potential for false alarms, it is essential that navigation officers are properly trained to effectively manage and prioritize alarm notifications. Effective communication and coordination among bridge team members is likewise critical in ensuring alarms are being responded to in a timely fashion and that appropriate actions are being undertaken to address any risks. Lastly, the effectiveness of alarm systems in ensuring maritime safety depends on the vigilance, skills, and collaboration of the navigation officers on board (Liu and Guo, 2023).

Alarm fatigue, a condition where too many or poorly prioritized alarms overload operators to the point where they react slowly, become situation-aware, and, in severe situations, ignore important notifications, is a problem that shipping is increasingly experiencing (Koppaka and Valsan, 2024). Human cognitive capacity is limited, as research indicates; persons are capable of processing five to nine pieces of information at a time. An excess of auditory alerts within high-stress operating conditions, such as those found on ship bridges, may cause tunnel vision, as operators fail to perceive key cues due to disjointed or overly focused attention (Boppudi et al., 2024).

Human cognitive capacity is limited in how many stimuli can be effectively processed at once. Nikkinen (2018) points out that most people can manage about five to nine items at a time, and when attention is focused too narrowly, important signals can be missed because of this tunnel vision. In this situation, too many or poorly prioritized alarms disrupt situational awareness, slow down reactions, and may cause navigation officers to override or ignore critical alarms that can affect the safety of navigation. Alarm fatigue can lead to frustration, loss in awareness, slower decision-making, and precipitate silencing of alarms, all of which threaten bridge safety (Kane-Gill et al., 2017). However, the usage of speech alarms, which substitute intelligible, natural-language messages for conventional beep tones, is one possible approach. Speech alarms can transmit precise information and directions, much like voice navigation systems like Google Maps (Xi, 2024). This could improve comprehension, lessen cognitive burden, and enable quicker and more precise operator replies. Speech alarms have the ability to enhance general situational awareness and decision-making in high-stress situations by offering context and real-time guidance. This technology has the potential to completely change how alerts are interpreted and handled across a range of industries, resulting in safer and more effective operations (Koppaka and Valsan, 2024).

To assess this problem, this research explores a new approach: replacing traditional beep alarms with speech alarms. These speeph alarms provide clear, natural-language instructions, similar to intelligent speech assistants like Google Maps. The goal is to make alarms more informative and easier to act on, reduce mental demand, physical demand, temporal demand and help navigation officers respond more quickly and accurately.

2- Research Background

2-1 Alarm Fatigue in Maritime Operations

Alarm supervision remains an actual problem in effective operation of navigation equipment. Low priority or overload alarms may put an important burden on the navigation officers, generating potential distraction and mental overload. Maglić (2020) authored that in a single typical watch, a navigation officers spend approximately 22.4 minutes managing 64 different actions triggered by 16 alarms. These repeated alarms not only demand much attention but also possibly divert attention away from important navigational tasks. Surprisingly, research indicated that 45% of these alarms were considered to be annoying and over-emphasized, even leading to alarm fatigue and reduced responsiveness to actually critical alerts. Such evidence emphasizes the need to improve alarm design and prioritization mechanisms to enhance situational awareness and overall navigational safety. (Maglić L, 2020). Alarm fatigue in maritime circumstances is a widely discussed safety concern. Lloyd's Register (2024a) found a 197% increase in audible alarms on ship bridge since the year 2000. Alarms are typically non-emergency or spurious and tend to be ignored or silenced by navigation officers. In 2017 bulk carrier grounded in Malacca Strait due to the disregard of depth warnings (MAIB, 2020).

According to InterManager (2019), 89% of navigation Officers often faced frequent distractions from alarms, and 66% felt that these alarms were not easy to identify or not important. Recent study demonstrated in figure 1 based on Lloyd’s Register (2025) viewed more than 40 million alarm-related events over 2,000 operational days from integrated automation systems of 11 commercial vessels. This huge dataset was compared with internationally recognized performance criteria as per IEC 62682:2014 and EEMUA 191, showing that the majority of alarms are far from the prescribed limits and, hence, there is a system inefficiency in bridge alarm configuration and prioritization (Lloyd’s Register, 2025). The findings support the necessity for context- dependent and human-centered alarm design, which, in turn, justify alternate developments such as speech alarms.

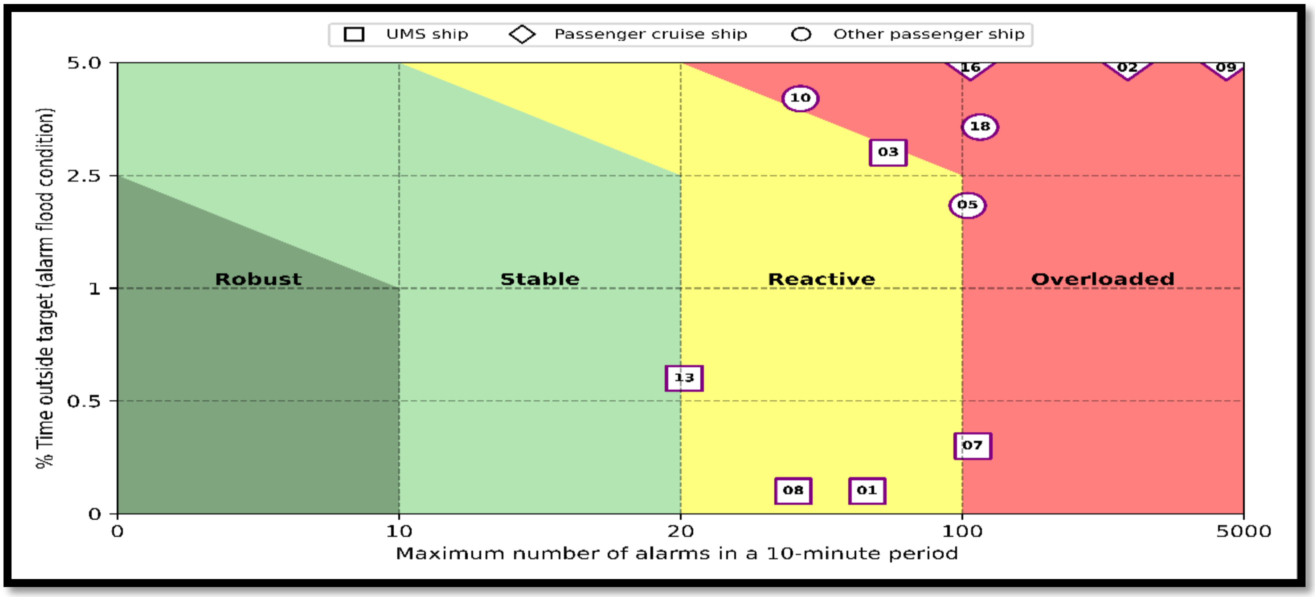


Figure 1: Alarm system performance in upset states for participating ship types
Source: (Lloyd's Register, 2025)

2-2 Alarm Fatigue in Other Sectors

Alarm fatigue is reported across various safety and critical sectors, where the accumulation of alarm leads operator to confusion, delayed responses or neglect alarm system. In healthcare, mainly in intensive care units (ICUs), research found that clinicians are often received plenty alarms per shift many of which are either false or non-important. Recent research by Cvach et al. (2022) demonstrate that such alarm overload has been directly linked to missed or delayed responses to critical events, eventually exposing patient care and medical outcomes. The aviation sector has challenged similar, mostly during important tasks such as takeoff or landing. Wu et al. (2024) assess several types of aviation alerts and found that numerous of ambiguous alarms lower the pilot performance and situational awareness. Their findings show how poorly designed alarm systems can lead to human error, especially when auditory participates with time-critical decision-making.

In recent years, much attention has been given to advances in alert management applied to reduce alarm fatigue in aviation and health care sectors. A hierarchical filtering of alarms, contextualized alerting, and a voice interface were all shown to reduce physical overload and improve an operator's decision-making ability (Wen et al., 2025; AHRQ, 2024). These techniques apply with much relevance to the maritime industry, where navigation officers face similar challenges while using bridge equipment during navigational watch, especially in coastal waters alarms increase that act negatively to erode the officers' situational awareness and ability to respond efficiently. Lloyd's Register (2024) suggests Learn from aviation, the time is ripe for the evolution of ECDIS alarms into more intelligent and user-focused systems. Latest update from IMO's S-100 framework and the structured integration of historical casualty data pave the way for smarter, context-aware alerts generated against a background of real-time environmental and navigational conditions (IHO, 2024; Lee et al., 2025).

2-3 Human Cognitive Response to Speech

Recent research by Wu et al. (2024) examined the impact of different alarm types ear cons, auditory icons, and speech alarms on pilot performance in aviation simulations. Their findings verified that speech alarms reliably produced lower cognitive workload, mental demand, physical demand and temporal demand as measured by NASA-TLX, and faster reaction times, the efficiency of speech alarm in working environments where timely decision-making is critical. In addition, Wickens' Theory which suggests that distributing tasks across separate cognitive channels such as speech instructions reduces information processing overload in maritime bridge operations, where navigation officers manage instantaneous tasks from radar, ECDIS, AIS, and VHF, speech alarms can consequently improve cognitive stress and enhance situational awareness (Shehata et al., 2023 ; Wickens et al., 2020). Also, the idea that speech alarm enhances task performance by reducing visual confirmation and allowing faster responses. This idea strengthens the case for integrating speech alarm systems in navigation environments to mitigate alarm fatigue and optimize human system interaction (Wu et al. 2024).

2-4 Google Maps as a Model for Speech Alarms

Google Maps delivers a familiar implemented model for real time speech navigational alarm, which can propose perceptions for bridge alert systems. Key features of Google Maps' voice interface include: Anticipatory phrasing for enhancing the probability of timely and accurate responses. Progressive prompting Instructions intensify as the decision point nears to ensure urgency is appropriately conveyed. Conversational tone for reduces user stress and avoids startling the driver, thereby improving user receptiveness and confidence (Google Design, 2024). These techniques can directly update the design of maritime speech alarm systems, especially within complex interfaces such as ECDIS. For example, instead of beep or visual indication, a speech alarm might announce: "Caution: crossing safety contour." Recent design principles by Google Design (2024) support natural voice language communications that prioritize user cognition and minimize mental and physical demand. These include voice recurrence options, customizable urgency sceneries, and human natural phrasing, all theoretically can be transferable to maritime alarming systems. Adopting such strategies would allow alarm systems to become more instinctive, less disturbing, and more actionable, thereby reducing alarm fatigue and enhancing situational awareness on the bridge team.

3- Literature Review

Previous research shows an overall congruence on the importance of developing speech alarm systems in high-risk industry such as the maritime sector, with a particular focus on the mental and physical impact of these systems on individual performance and operational safety. (Kim, J. and Song, H., 2024) established the efficiency of user-generated speech alarm in enhancing awareness and accomplishing successfully daily tasks. These outcomes are consistent with what was shown by (Deschamps et al., 2024) that showed that sounds designed in a qualitative and specific manner improve response and reduce mistake in identifying an occurrence compared to beep alerts or traditional alerts. These results support the findings of (ASALOMIA et al., 2025) that used artificial intelligence to evaluate and classify maritime alerts, as it demonstrated that precise classification and intelligent alerting improve situational awareness, which contributes to supporting effective decision-making.

On the other hand, the most prominent (Kuparinen-Koho 2020, Dewi 2025), such as the importance of taking into account human factors and complex digital environments, showed that poor system design and increased complexity lead to a deterioration in situational awareness and increased mental stress and technical fatigue among users, which intersects with the results of (Öcal 2025) where it was found that excessive reliance on digital systems without sufficient arrangement leads to unsafe behaviors and a decline in the efficiency of maritime surveillance. Although the study does not directly address the navigational context, the communications emphasizes the importance of self-awareness and methodology in conducting field awareness in a sensitive environment, which is an aspect that can be used methodologically to understand the psychological and mental contexts of navigational officers when exposed to a high density of alerts. Therefore, there is agreement among furthermost research that designing speech alert systems in a clear, directed manner that considers human factors can increase awareness, reduce incidents, and improve safety. Furthermost likewise approve that poor training, excessive confidence on technology, and poor interface design epitomize extreme challenges that must be addressed. After the researches focused on alert systems in healthcare, while others focused on the maritime sector, but taken together they provide a solid scientific framework to support the importance of targeted speech alerts as a means of improving decision making, situational awareness and safety in the maritime industry.

Researches illustrate cumulative concentration in the problem of alert fatigue and mental load linked with critical work environments, especially in intensive care units and vessel navigation bridges, where conditions are considered by dense information, restricted time, and quick decision-making. (Shanmugham et al., 2018, Seok et al., 202, Salameh et al., 2024, Guo et al., 2021) agree that frequent alerts that are not designed according to human factors principles contribute directly to increased cognitive load, which negatively affects employee performance and increases the probability of human error.

In addition, (Shanmugham et al., 2018) demonstrate that regulating clinical alert settings based on the patient's condition directed to a decrease in mental load and an improve decision making, which meets with the outcomes presented (Guo et al., 2021) on the importance of informal and resilient design in vessel navigation bridges to reduce mental load and improve response in emergency situations.

Despite the diversity of researches that have addressed the topic of alert fatigue, mental load, and the impact of alert interface design on human performance, there are several aspects that still need in-depth study. First, most of the literature focuses on medical environments such as intensive care units, while navigational environments, especially the navigational bridge environment, are almost absent from the study in terms of experimental analysis of the effect of alert density on navigational officers while performing tasks in realistic or simulated scenarios. Second, there is a deficiency of researches that demonstrate the efficiency of speech alerts compared to traditional beep alerts in relations of their impact on quick decision making, high level of situational awareness. The literature also demonstrates the lack of navigation officers in perceive and process different types of alerts under conditions of time and information pressure. Third, most studies do not adopt an integrated methodology that combines self-assessments of mental impairment, such as the NASA-TLX scales, and behavioral indicators such as response time. Psychological indicators such as stress and mental fatigue in the contexts of field work or realistic simulation, especially in maritime environments. Fourth, theoretical frameworks think of comprehensive models that link alert systems, human factors, mental and behavioral performance, and the level of operational safety. There is also a deficiency in integrating these concepts within training and operational policies specific to the field of maritime navigation, which limits the effectiveness of applying human-centered design concepts in improving the efficiency and safety of navigation operations.

This study addresses an important gap in the existing literature through an empirical examination of the effectiveness of speech alert system in a vessel marine bridge setting, to date a topic not fully researched. It presents experimental evidence that shows speech alerts alleviate mental demand and improve physical demand, temporal demand, improve situation awareness and decision making compared to beep alerts. It also emphasizes the importance of including human factors in alarm system design and provides working guidance to advise and support maritime training.

4- Methodology: Evaluating Speech Alarms in ship Bridge Operations

This experiment uses a multimethod experimental design consisting of performance based quantitative measures with objective data and e-based qualitative measures to determine the effectiveness of speech alarms for ship bridge operations. Twelve navigation officers with sea experience were randomly assigned to control and experimental groups to which they were subjected to traditional beep alarms and to speech alarms, respectively. Solo simulation scenario was conducted by each subject on a full-mission bridge simulator at AASTMT, configured to simulate real-world maritime conditions. Objective metrics response times and number of accepted alerts were collected through simulator logs. Subjective cognitive workload was measured after scenario completion by the NASA Task Load Index (NASA-TLX), a subjective measure of perceived workload across six dimensions. Performance was further analyzed by assessing the association of frustration ratings with task performance using the Pearson’s correlation coefficient. This methodical approach allowed for the collective assessment of the impact of different alarm modalities on daily performance and mental workload in the ship bridge operations.

4-1 Participant Profile and Scenario Development

Twelve navigation officers who had attended Bridge resource management course trainings at AASTMT participated in the research, all participants had sea experience. participants were randomly assigned into two equal groups: Control Group (exposed to traditional beep alarms) and Experimental Group (exposed to contextual speech alarms). A simulation of a bridge navigation was performed by each of the navigation officers individually to reduce the effect of groupthink on decision making. Two scenarios were generated and executed using AASTMT full-mission bridge simulator: one of them representing normal sea conditions that might typically be encountered during maritime operations and the other representing poor sea conditions with: Moderate traffic, Complexity of environmental conditions, and the Common ECDIS, radar and engine alarms. The simulation was controlled by two instructors to maintain identical timing and content of critical alerts across both groups. In the beep group, alerts were communicated with traditional beeps. In the speech group, the instructor delivered real-time speech alerts via intercom using natural, context-rich phrases.

4-2 Data Collection Tools

To assess both objective performance the following tools were used:

- Simulator logs to record: Reaction times to alerts and Number of acknowledged responses
- (NASA-TLX) questionnaire, was applied in the end of simulation scenario to evaluate six dimensions of perceived: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration to assess the subjective cognitive workload experienced by participants, the research applied the (NASA-TLX) a widely validated tool in human factors research. After finishing each simulation scenario, participants rated each dimension on a scale from 0 (low) to 100 (high), providing a complete profile of their perceived workload. This method allows to comprehend how different alarm impact mental stress and decision-making effort. NASA-TLX is generally appropriate in maritime studies, where high-stress industry and complex multitasking are communal. Its presence in this research enhances the strength of the findings by relating objective performance data with subjective human experience.

4-3 Performance Metrics

The following dependent variables were used to compare two groups performance:

Table 1: Performance Metrics

Metric	Description
Reaction Time	Time (in seconds) from alarm onset to corrective action initiation
Acknowledged Responses	Count of alarms that were responded to correctly within a reasonable timeframe
Subjective Workload (NASA-TLX)	Scores from 0–100 for each cognitive demand dimension, self-reported by officers' post-task

Metric	Description
Frustration-Performance Correlation	Pearson correlation used to explore the relationship between perceived frustration and performance outcomes

This structured approach allowed for a strong comparison between beep and speech alarms, evaluating both task efficiency and cognitive impact under operational conditions.

5- Analysis and Results

The simulator experiment intended to compare the effectiveness and cognitive impact of beep alarms against speech alarms during bridge operations. total of 12 licensed navigation officers participated in the research, with 6 officers randomly assigned to each group (beep alarms vs speech alarms). Navigation officers in the research, consistently divided between (beep alarm group) and (speech alarm group). Independent samples t-tests were conducted to determine the significance of differences in reaction times and Acknowledged Responses between the two groups.

Table 2: Independent Samples t-Test: Reaction Time and Acknowledged Responses

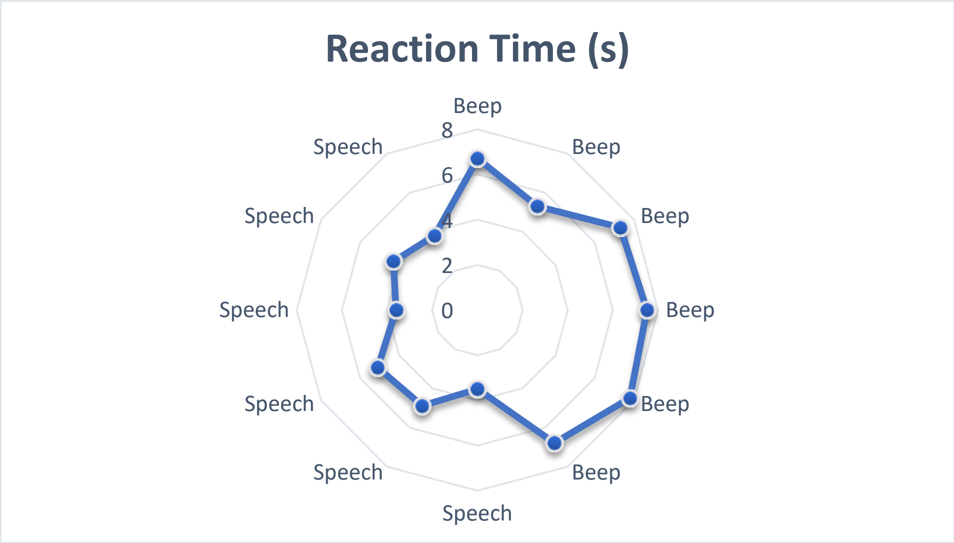
	Test Value = 0					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
Reaction Time Beep	19.040	5	.000	6.90000	5.9684	7.8316
Reaction Time Speech	15.103	5	.000	4.20000	3.4852	4.9148
Acknowledged Responses Beep	5.736	5	.002	7.16667	3.9549	10.3785
Acknowledged Responses Speech	35.383	5	.000	22.03333	20.4326	23.6341

5-1 Reaction Time

Reaction time, defined as the interval between alarm activation and the officer's initiation of corrective action, was expressively lower in the speech alarm group. The mean reaction time is higher for the Beep group (6.90 s) compared to the Speech group (4.20 s). The standard deviation is higher for the Beep group (0.89 s) compared to the Speech group (0.68 s). This reduction shows that speech alarms provided clearer and more instantly actionable information and earlier responses.

Table 3: Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
Reaction Time Beep	6	5.30	7.80	6.9000	.88769
Reaction Time Speech	6	3.50	5.10	4.2000	.68118
Valid N (listwise)	6				



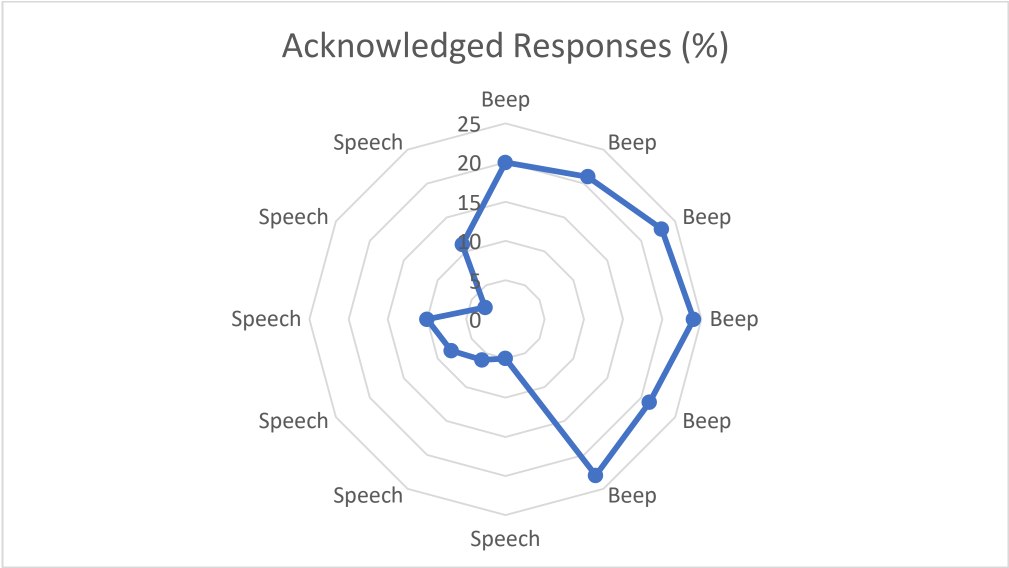
Graph 1: Reaction Time

5-2 Acknowledged Responses

Navigation officers Participate in the speech alarm group effectively acknowledged more critical alarms compared to navigation officers participate in the beep alarm group. On average, navigation officers using speech alarms responded to 22.03 alarms, while those using beep alarms responded to only 7.17 alarms during the simulation scenario. This result indicates a considerable enhancement in attentiveness and responsiveness under speech guidance. The standard deviation was lower in the speech group (1.53) than in the beep group (3.06), suggesting more consistent performance among navigation officers using speech alarms. This difference suggests that speech alarms mitigate the desensitization associated with alarm fatigue by enhancing message clarity and urgency. Also help reduce cognitive overload and alarm fatigue by delivering clearer, more actionable messages.

Table 4: Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
Acknowledged Responses Beep	6	3.00	11.00	7.1667	3.06050
Acknowledged Responses Speech	6	20.00	24.00	22.0333	1.52534
Valid N (listwise)	6				



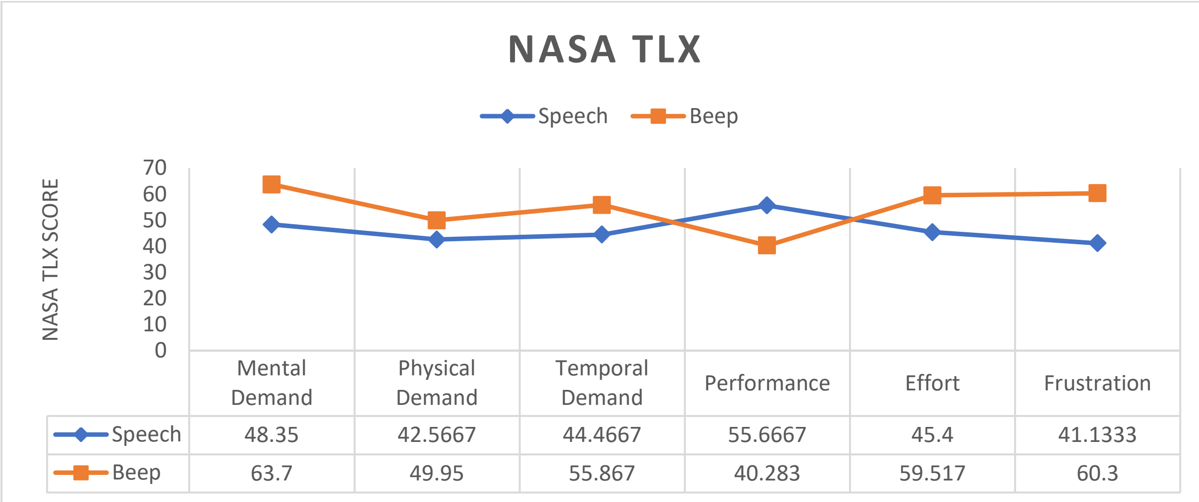
Graph 2: Acknowledged Responses (%)

5-3 Subjective Workload (NASA-TLX)

The NASA Task Load Index (NASA-TLX) was administered to assess perceived cognitive workload across six dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration.

Table 5: Descriptive Statistics

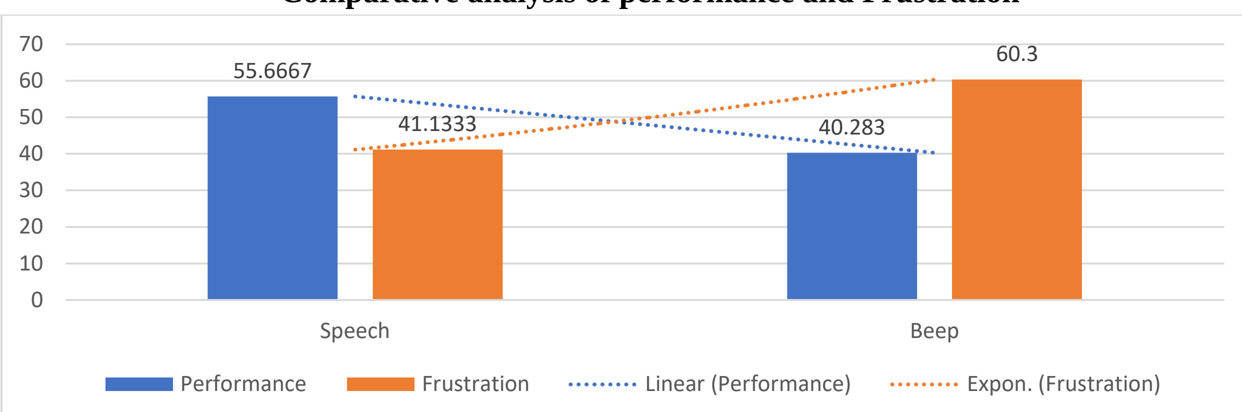
	N	Minimum	Maximum	Mean	Std. Deviation
Mental Demand Speech	6	46.80	50.10	48.3500	1.18110
Mental Demand Beep	6	60.3	66.4	63.700	2.1679
Physical Demand Speech	6	40.30	44.00	42.5667	1.33816
Physical Demand Beep	6	47.9	52.3	49.950	1.6171
Temporal Demand Speech	6	42.50	46.10	44.4667	1.22746
Temporal Demand Beep	6	53.1	58.6	55.867	1.9796
Performance Speech	6	53.60	57.40	55.6667	1.36039
Performance Beep	6	38.4	42.5	40.283	1.4386
Effort Speech	6	43.90	46.90	45.4000	1.09179
Effort Beep	6	57.6	61.0	59.517	1.3977
Frustration Speech	6	39.40	42.30	41.1333	1.07269
Frustration Beep	6	58.9	62.1	60.300	1.2665
Valid N (listwise)	6				



Graph 3: NASA TLX

Regarding graph 3 demonstrated that, the Beep group generally experienced higher levels of workload, as indicated by higher means in Mental Demand, Physical Demand, Temporal Demand, Effort, and Frustration. Regarding Performance Differences, the Speech group revealed better Performance and a higher percentage of Missed/Delayed Responses compared to the Beep group. Regarding Reaction Time, participants in the Beep group had a slower Reaction Time compared to those in the Speech group.

Comparative analysis of performance and Frustration



Graph 4: a comparative analysis of performance and Frustration

Graph 4 presents a comparative analysis of performance and Frustration between participants exposed to traditional beep alarms and those exposed to speech alarms during bridge simulator exercises.

Interpretation of Correlation: Negative Correlation is evident between Performance and Frustration. The correlation coefficient of −0.97 indicates a very strong negative linear correlation between Performance and Frustration. As frustration decreases, performance improves. This supports the hypothesis that replacing beep alarms with speech alarms can reduce cognitive load and improve operational effectiveness on ship bridges.

Table 6: Correlations Analysis

		Performance	Frustration
Performance	Pearson Correlation	1	-.979**
	Sig. (2-tailed)		.000
	N	12	12
Frustration	Pearson Correlation	-.979**	1
	Sig. (2-tailed)	.000	
	N	12	12

**. Correlation is significant at the 0.01 level (2-tailed).

1. Reaction Time (seconds): Participants using speech alarms responded earlier (4.2 seconds) compared to those using beep alarms (6.9 seconds), suggesting that speech alarms provide clearer and more actionable information.
2. Missed or Delayed Responses (%): The beep group missed or delayed 22% of critical alarms, while the speech group had a much lower rate at 9%, indicating improved attention and response consistency with speech alerts.
3. Mental Demand (NASA-TLX Score): Navigation officers using beep alarms reported a mental demand score of 63.7**,** whereas those using speech alarms reported 48.3, showing that speech alarms reduce cognitive strain.
4. Effort: navigation officers in the beep group reported expending more effort (59.8) than those in the speech group (45.5), indicating a smoother workload in the latter condition.
5. Frustration: Frustration levels were substantially higher for the beep group (60.1) compared to the speech group (41.2), suggesting that traditional alarms contribute more to stress and confusion.

5-4 Qualitative Feedback

The speech group’s navigation officers felt more familiar with speech alarm. Improved alert specificity and clarity, less reliance on visual confirmation, increased confidence in situational awareness, and less discomfort than with a loud beep alert. The beep group, on the other hand, reported having trouble interpreting the significance of alarms without checking radar or ECDIS systems, experiencing alarm overload, and becoming confused during simultaneous alerts.

5-5 Observational Insights

Simulator logs shows that navigation officers in the speech group made fewer course corrections due to quicker decisions and increase accuracy in traffic avoidance maneuvers. Their bridge team management also improved, as speech alerts allowed better coordination and reduced redundant verbal communication between bridge team members. The simulator-based experiment provides strong evidence that speech alarms improve navigational performance and reduce cognitive load. The observed benefits include: faster and more accurate responses to incidents, fewer missed alerts, lower subjective workload, and higher operator satisfaction. These findings strongly support the integration of speech-based alerts into modern bridge systems, especially in industry with high-frequency alerts.

6- Discussion

The Operational Benefits of Speech Alarms that provide immediate contextual understanding, improve bridge team confidence in alert systems, and reduce cognitive strain and decision-making delay time. The speech alarm could particularly decrease incidents involving underestimated vessel maneuverability, ignored ECDIS or RADAR alerts, or misread engine warnings. Regarding design considerations, effective implementation of using IMO-standard Maritime English, modular alert severity, tone, context, and configurability language, voice gender, and frequency. For example, “Warning: crossing safety contour.

There are a few lessons to be learned from some of the most prevalent voice technologies such as Google Maps and other AI assistant platforms. They service a measured and informative tone with modulation intended to impart expressive data without imparting anxiety or distraction. In being in maritime settings, having a similar approach will assist one in remaining calm and level-headed in possibly high-stress circumstances. Key principles are maintaining a consistent and not startling tone, issuing segmented warnings that incrementally build up to critical warnings, and incorporating options for users to replay or request repetition of messages when needed. These features ensure that speech alarms not only alert but also improve decision-making, just as the friendly and reassuring attributes have contributed to voice assistants' popularity elsewhere.

7- Recommendations

Based on the findings of this study, several recommendations are proposed to enhance navigational safety through the adoption of speech alarm utilization. Initially, it is recommended that the International Maritime Organization (IMO) consider revising existing regulation, particularly MSC.302(87), to expansively incorporate speech alarm utilization provisions in the conduct of bridge operations. At the same time, bridge system original equipment manufacturers (OEMs) need to be encouraged to incorporate speech alert modules into their equipment packages to encourage universal adoption. Second, implementing a standardized protocol for maritime speech-based alarms based on ISO/IEC standards would encourage consistency and compatibility with diverse vessels and systems. Training schools must also incorporate speech alarm systems into simulator-based training courses and the respective modules of the Standards of Training, Certification and Watchkeeping (STCW) to familiarize navigation officers with this technology and its implications for use. Last but not least, further human factors research is required, including longitudinal studies to further evolve speech interaction patterns, assess their long-term efficiency, and identify cultural and linguistic compatibility across the globally diverse maritime workforce. These collective measures could mitigate alarm fatigue and enhance safety in modern ship bridge operations.

Alarm fatigue is prevalent, with a majority reporting frequent exposure and negative impacts on awareness. Auditory overload leads to ignored alarms, reducing the effectiveness of bridge monitoring systems. Beep alarms lack clarity, especially under high-stress or complex navigational conditions. Officers show a strong preference for speech-based alerts, associating them with improved clarity and prioritization. Recommendation include Pilot studies using speech-based alarms in bridge simulators or training ships may validate these findings before fleet-wide implementation.

8- Conclusion

Alarm fatigue is increasing the risk factor in bridge navigation, undermining safety by dulling the human response to critical signals. Drawing from successful speech assistance platforms like Google Maps, this study demonstrates the potential for speech-based alarms to alleviate cognitive burden, increase clarity, and improve timely decision-making. The maritime industry stands at the cusp of a new era in alert design one that should prioritize context, clarity, and human-centered communication.

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Embedding Green Education in Maritime Curricula: Advancing Environmental and Maritime Sustainability

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المستخلص

في هذا البحث تم التحقيق في الآثار المتعددة لدمج التعليم الأخضر ضمن مناهج التعليم والتدريب البحري. ومع مواجهة القطاع البحري لتعقيدات الاستدامة البيئية والتطورات التكنولوجية في عصر الثورة الصناعية الرابعة، يصبح تعزيز جيل جديد من المتخصصين الواعين بيئيًا أمرًا بالغ الأهمية. اعتمد هذا البحث المنهج النوعي لتقييم شامل للفوائد والتحديات والعوائق المحتملة المرتبطة بدمج التعليم الأخضر في برامج التعليم والتدريب البحرى ومن خلال مراجعة الأبحاث العلمية وآراء الخبراء، عرضت الورقة نهجًا تكامليًا يعزز استدامة البيئة البحرية وتطور القطاع البحري، إضافةً إلى التخفيف من التعقيدات التربوية والمؤسسية والعملية. وأظهرت النتائج معرفة معمقة تفيد المؤسسات العلمية البحرية وصانعي السياسات وأصحاب المصلحة في الصناعة لزيادة فعالية أثر دمج التعليم الأخضرفى منهاج التعليم والتدريب البحرى.

Abstract

This research examined the multiple effects of integrating green education into Maritime Education and Training (MET) curricula. As the maritime sector faces the complexities of environmental sustainability and technological progress in the era of Industry 4.0, fostering a new generation of environmentally conscious professionals becomes essential. This study used a qualitative approach to thoroughly assess the benefits and potential challenges and barriers of incorporating green education in MET. By reviewing scholarly publications and empirical studies, the paper presented an integrated approach that promotes the sustainability of the maritime environment and advances the maritime sector, while addressing pedagogical, institutional, and practical challenges. The findings provided valuable insights for educators, policymakers, and industry stakeholders to enhance the effectiveness of green education frameworks in MET.

1- Introduction

The maritime industry, which is the backbone of global trade and the global economy, including shipping, seaport, and shipbuilding (Sullivana et al., 2020) and economic development, is simultaneously a significant contributor to environmental impacts, including greenhouse gas emissions, marine pollution, and habitat degradation. At the same time as rising environmental challenges globally and tight international laws, the maritime sector is undergoing a transformative shift towards sustainability. This paradigm shift needs a critical examination of the current processes, technologies, and the education and training of future maritime professionals.

Environmental education, also known as green education or education for sustainable development, is an invaluable tool to equip such professionals with the knowledge, skills, and attitudes they possess to lead and influence such a shift with effectiveness (Simanjuntak et al., 2024; Hardian et al., 2024). The integration of green education into MET curricula is not only an academic work but also a strategic essential. It aims to cultivate an in-depth understanding of ecological principles and promote sustainable operational approaches among seafarers and maritime stakeholders. Nevertheless, the incorporation of this elaborate and dynamic notion within existing frameworks of education is accompanied by positive potential as well as considerable challenges. This research paper attempts to present an in-depth and critical examination of these positive and negative effects through qualitative and argumentative analysis from academic literature.

2- Methodology

This research paper employs a qualitative methodology to explore the positive and negative impacts of embedding green education within MET curricula. The qualitative approach is particularly suited to this study, as it allows for an in-depth understanding of complex phenomena, perceptions, and experiences related to the integration of sustainability in education (Padgett, 2016; Saldana, 2014). By focusing on the 'how' and 'why' of green education's impacts, this methodology facilitates a nuanced exploration of the argumentative aspects derived from academic work.

The research design primarily relies on a comprehensive narrative review of existing scholarly studies and reports related to the topic. Additionally, several case studies and empirical data from various countries are incorporated. This approach enables the synthesis of different perspectives, highlights key themes, and develops an argumentative narrative about the impacts of green education in MET. The literature review method is especially effective for examining complex educational and environmental issues where empirical data collection may be impractical or where a broad overview of existing knowledge is required (Yilmaz, 2013).

This study will examine the following major elements:

- Foundations of green education and sustainable development applied to the shipping sector.
- The positive impact of environmental education in enhancing knowledge of the environment, stimulating sustainable behaviour.
- The negatives and challenges include pedagogical challenges, resistance to reform, and resource limitations.
- Validating the findings through multiple empirical studies across developed countries.

A qualitative approach based on a thorough review of existing literature will be employed to synthesise knowledge and provide a critical analysis. Ultimately, the aim of this research is to enhance understanding of how green education can be effectively integrated through MET, promoting a more sustainable future for the maritime sector.

3- Literature Review

3-1 Green Education and Sustainable Development in the Maritime Context

Green education is a learning approach that integrates environmental sustainability principles and practices within educational frameworks. The main goal is to equip seafarers with the necessary knowledge, skills, and attitudes to address environmental challenges and promote sustainable development (Hardian et al., 2024). In the maritime context, it involves understanding marine ecosystems, pollution prevention measures, sustainable resource management, and international environmental regulations (e.g., MARPOL) (IMO, 2018; UN, 2015). The primary aim is to cultivate a new generation of maritime professionals committed to environmental protection and sustainable development principles (Simanjuntak et al., 2024).

Sustainable development was defined as development that meets present needs without depriving future generations of their ability to meet their needs (Brundtland Commission, 1987). For shipping, the principle involves incorporating environmental protection, social responsibility, and economic viability into all maritime activities (IMO, 2020; Soltani Motlagh et al., 2023). These actions include efforts to enhance the environmental efficiency of international shipping, reduce greenhouse gas emissions from ships, and sustain the long-term health of marine ecosystems.

3-2 The Role of Green Education in Fostering Sustainability in MET

The integration of green education in the MET is fundamental to preparing future maritime professionals equipped with skills and competencies to navigate the complexities of an industry in rapid transformation. The process involves embedding sustainability concepts in the curricular design, pedagogic practices and assessing measures (Simanjuntak et al., 2024).

Traditionally, maritime education has focused on the acquisition of technical skills regarding navigating and management of shipping (Walker et al., 2010; Harrison, 2009). However, a significant gap has emerged, necessitating the embedding of environmental education into the maritime curricula. This integration is intended to align education programs with sustainable development goals and deliver maritime professionals who are environmentally responsive (Simanjuntak et al., 2024). The knowledge gap is visible across various fields: traditional maritime education curricula have often avoided the environmental dimensions of the industry, leaving professionals well-skilled in operational issues but lacking in an understanding of ecological awareness (Chakraborty, 2021; Stokols, 2018). Furthermore, there is a growing demand for maritime professionals who are not just technically equipped but also environmentally literate in a holistic understanding (IMO, 2018; UN, 2015). A lack of standard environmental education across maritime courses has also helped to create differences in training and varying levels of environmental awareness among seafarers (Simanjuntak, 2023).

3-3 International Frameworks and Green Education in MET

The International Maritime Organization (IMO) has played a vital role in creating frameworks for sustainability within the maritime sector. While it has traditionally focused on technical skills (IMO, 1996), the Manila Amendments in 2010 seek to equip seafarers with knowledge about sustainability objectives (IMO, 1996, 2010b). However, Sustainability Thinking—covering essential non-technical skills such as leadership and teamwork—is often overlooked and not explicitly recognised in international standards like STCW and the International Safety Management (ISM) code (IMO, 2018). This highlights a gap in the standards concerning the development of robust methods for assessing sustainability thinking in maritime education and training (MET) (Simanjuntak et al., 2024).

The IMO has not yet established a definition for 'Sustainability' but has initiated proactive efforts to enhance the environmental performance of international shipping, reduce emissions, and attempt to develop sustainability by integrating environmental management and economic feasibility into maritime operations (IMO, 2020; Soltani Motlagh et al., 2023).

3-4 Positive Impacts of Green Education in MET

The embedding of green education into MET curricula provides beneficial effects, playing an important role in the environmental and maritime sectors' sustainability. These impacts can be primarily classified as improved environmental awareness, the encouragement of sustainability practices, and ecological protection responsibility.

a- Enhanced Environmental Awareness

Green education primarily aims to develop environmental awareness concerning challenges and their relevance in the shipping industry. By including subjects such as marine ecosystems, climate change, prevention of pollution, and global warming challenges, MET programs can significantly assist students in developing their understanding of the environmental impact of shipping activities (Hardian et al., 2024). This foundation helps equip professionals to develop an understanding of environmental hazards, comprehend regulatory needs, and value the sensitivity of marine ecosystems.

b- Promotion of Sustainable Practices

Green education, which encompasses knowledge and skills, is essential for applying sustainable development to the shipping industry. It includes training in green technology, energy efficiency, waste disposal, and the efficient use of renewable resources. Embedding environmental elements into maritime curricula enables MET institutions to graduate professionals who can reduce the environmental impact of the shipping industry. Practical training, real-world application, and discussions on current environmental challenges are highly beneficial for maritime students to develop their understanding and application of sustainability fundamentals (Simanjuntak et al., 2024).

c- Ecological Protection Responsibility

Green education at MET is vital for fostering ecological responsibility, which involves understanding the duties and rights of stakeholders towards the environment (Hardian et al., 2024). This includes promoting a shared responsibility for environmental protection and sustainability, and supporting ethical decision-making and commitment to sustainability. By empowering students to act as environmental guardians both within and outside the workplace, MET programs help build a workforce for whom environmental responsibility is a core professional value. The United Nations Sustainable Development Goals (UN-SDGs), particularly SDG 4 (Quality

Education) and SDG 14 (Life Below Water), provide an international framework for addressing these issues, and green education at MET directly contributes to achieving these Goals by encouraging responsible management of marine resources and ocean conservation (UN, 2015; Simanjuntak et al., 2023).

3-5 Negative Impacts and Challenges of Green Education in MET

Despite the obvious merits, integrating green education into MET curriculums faces several challenges and potential barriers. These include pedagogic and institutional obstacles, as well as resistance from traditional paradigms and resource constraints.

a- Pedagogical and Curricular Barriers

One of the main challenges is the pedagogic approach and curriculum framework. Most existing academic frameworks, though historically informative, tend to overlook or inadequately address the key implications of automation, digitalisation, and autonomy (Elmeligy, 2025). There is also a lack of standardised green education frameworks, which leads to uneven training and varying levels of environmental literacy among students from different institutions (Simanjuntak, 2023). Saylan's (2011) highlights the fact that awareness alone does not lead to action, and environmental education often fails to be meaningful.

b- Institutional and Resource Constraints

MET institutions for the Maritime Sector often face resource constraints, including a lack of funds, inadequate physical facilities, and a shortage of educators skilled in sustainability within maritime activities and environmental awareness (Siahaan et al., 2024; Chakraborty, 2021; Stokols, 2018). Developing innovative green curricula requires substantial financial investment in teaching resources, technological upgrades, and teachers' professional development. Additionally, resistance to changing traditional pedagogic models can pose a significant barrier.

c- Academic and Industry Alignment

There is a considerable gap between MET institutions and industry needs in practice, due to the absence of a harmonised maritime taxonomy integration framework (Elmeligy, 2025). This disconnection may lead to graduates who are inadequately skilled with the green competencies required by a transforming industry, or an industry evolving to become greener because of a perception of unqualified personnel (Saylan, 2011).

d- Risk of Superficial Implementation

In some cases, the green education process can be applied superficially, focusing on guideline following rather than genuine understanding and behavioural change. This approach may involve going through the motions, with environmental courses delivered without full engagement or critical analysis. When it concentrates only on abstract structures without real-world application, it might be seen as less effective in fostering sustainability thinking (Simanjuntak et al., 2024).

4- Validation from an Empirical Perspective

The shift towards sustainability in the maritime industry involves not only advanced technology but also transforming maritime training and education systems. Therefore, green education is vital in integrating into educational curricula, policy frameworks, and among industry stakeholders. Many countries aim to speed up workforce adaptation to sustainability by including green education in their systems.

In Norway, they incorporated green maritime education into the government's electrification policy to boost practical efficiency. MET institutions worked with ferry operators to provide training modules on high-voltage (HV) safety, battery management, and related topics. Sæther & Moe (2021) tested this initiative using mixed methods, including stakeholder interviews and policy analysis. The authors showed that the synergy between national decarbonisation policy and green maritime education greatly improved operators' skills and competencies, thereby increasing workforce readiness.

Another piece of empirical evidence came from the United Kingdom (UK) through a case study at the Port of Plymouth. This study supports the link between maritime green education and operational decarbonization. Karamperidis et al. (2023) conducted this research to show the impact of the short courses (e.g., emissions management, fuel safety, and energy efficiency) on the practical missions. The case study results assessments showed an improvement in operational performance and upskilling the personnel with the required competencies for sustainability.

Continuing with the UK, which examined the Skills for Green Jobs by combining a large-scale employer survey (n=620) with pilot implementations in three maritime education institutions. The results showed shortages in skills related to emission monitoring and the use of low-emission tools. Additionally, the employers who completed their green modules reported greater confidence in green competencies (Maritime Skills Commission, 2024).

Similarly, the Maritime Industry Authority (MARINA) in the Philippines initiated a real-world case study to support green education capacity-building. This study focuses on training more than 150 trainees in decarbonization awareness and green operations through short courses. Pre- and post-assessments have been conducted, indicating a dramatic increase in skills and competencies. This study bridged the gap between the international standards and the local application via the green maritime education (MARINA, 2023).

On a global scale, classification societies such as DNV applied an empirical assessment of the future needs of seafarers' training. This assessment includes topics such as decarbonization, emissions, green operation and sustainability. Sixty stakeholders were interviewed, and their responses emphasised that most seafarers would require new training to equip them with the skills and competencies necessary for areas such as high-voltage systems, carbonisation systems, and fuel reduction. Consequently, for example, maritime decarbonization not only relies on advanced technology but also on the capacity of green maritime education (Antoni Kaspersen et al., 2022).

These empirical studies used statistical analysis of their findings to demonstrate that embedding green education positively enhances MET institutions' ability to achieve sustainability in the maritime sector, as shown in Table 1.

Table 6: Stakeholder-Level Impacts of Green Maritime Education.

Stakeholder	Main Benefit	Example Study	Observed Result
Students / Cadets	Improved sustainability literacy and operational readiness	MARINA (2023)	40 % skill improvement post-training
Seafarers	New competencies in low-emission operations, HV safety	Antoni Kaspersen et al. (2022)	75 % required retraining in green competencies
Industry Stakeholders	Enhanced efficiency and decarbonization readiness	Karamperidis et al. (2023)	25 % fuel-use reduction at Port of Plymouth
Academia	Integration of sustainability in curricula and pedagogy	Sæther & Moe (2021)	3 new green courses introduced nationally

5- Discussion and Recommendations

The incorporation of green education within MET curricula presents a variety of potential benefits and barriers, as the earlier exploration of both advantages and constraints effects indicated. This section outlines these findings and identifies efforts to capture green education's benefits most effectively and mitigate its problems.

Research demonstrates that green education significantly boosts environmental awareness among seafarers (Hardian et al., 2024; Simanjuntak et al., 2024). However, awareness alone does not necessarily lead to action, as Saylan (2011) suggested. MET training should shift from just providing information to promoting application, critical thinking, and responsible decision-making. The focus should be on developing professionals who are environmentally educated and motivated to adopt sustainability practices. A curriculum that combines theory with practical skills is also crucial for students to make a real impact on the environment.

Another challenge was identified and clarified as the gap between academic institutions and the practical requirements of the maritime industry (Elmeligy, 2025). This disconnection can result in graduates who are not fully equipped with the necessary green skills and competencies aligned with industry advancements. To address this barrier, it is essential to focus on collaboration between MET institutions and industry bodies. This includes curriculum development that emphasises sustainable maritime practices relevant to the industry, and the enhancement of internship opportunities that give students a deeper understanding of environmental challenges and solutions. Furthermore, professional development for existing maritime personnel, also designed collaboratively with industry involvement, can help close the skills gap and promote the adoption of sustainability practices.

Shortages of professionals in MET institutions and resource limitations are significant obstacles to the widespread and effective implementation of green education (Siahaan et al., 2024; Chakraborty, 2021; Stokols, 2018). Overcoming these challenges requires a coordinated approach. Primarily, there is a strong need for increased funding and investment in MET institutions, especially for green education initiatives, including infrastructure upgrades, the development of innovative teaching materials, and faculty training. Additionally, cultivating a culture of innovation and flexibility within such institutions is essential. This involves encouraging teachers to adopt modern pedagogic techniques and providing them with the necessary support and training. Moreover, policy frameworks at both national and international levels can play a crucial role in facilitating the transition to green education and establishing guidelines for its integration, thereby reducing resistance to change and promoting a unified approach across the sector.

The superficial application of green education highlights the high risk and underscores the need for a holistic integration of green education in MET. Instead of teaching environmental topics as isolated courses, sustainability concepts must be incorporated throughout the entire MET curriculum, from basic modules to advanced training. This means embedding green education not only in environmental science courses but also across all maritime subjects (e.g., navigation, engineering, logistics, and maritime law). A holistic approach ensures that sustainability principles become part of the mindset of all professionals in the shipping industry, thus influencing decision-making at various levels.

6- Conclusion

Integrating green education into Maritime Education and Training (MET) curricula is a vital step to promote environmental sustainability and the sustainable development of the maritime industry. This study assessed the benefits and barriers of this integration using a qualitative narrative approach.

In conclusion, the benefits of green education for MET are significant and essential for a sustainable future in shipping, and achieving them requires a collaborative, strategic effort. This involves shifting to action-oriented teaching methods, fostering collaboration between academia and industry, securing adequate resources and institutional support, and applying sustainability principles holistically across the curriculum. By addressing the challenges proactively, MET institutions can play a key role in developing a generation of shipping professionals who are not only technically proficient but also deeply committed to environmental responsibility and the long-term sustainability of ships and the global shipping industry.

Finally, presenting multiple empirical studies provides strong validation for this research. It demonstrates the impact of incorporating green education within MET institutions, helping them to improve and achieve the Sustainable Development Goals (SDGs) in the maritime sector.

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The Impact of Smart Technology on Improving Energy Efficiency, Reducing Emissions in Egyptian Ports. Case study of Damietta port

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المستخلص

تُعد التجارة الخارجية عنصرًا أساسيًا في دعم اقتصادات الدول، وتلعب الموانئ البحرية دورًا محوريًا في هذا المجال، خاصة في مصر التي تتميز بموقع استراتيجي يربط بين أهم طرق الملاحة العالمية. ويُعد ميناء دمياط من الموانئ الحيوية التي تسهم في حركة التجارة الخارجية، إذ تمر عبره نحو ٩٠% من البضائع المصرية. إلا أنه يواجه تحديات تتعلق باستهلاك الطاقة، والانبعاثات، وكفاءة العمليات اللوجستية.

وتهدف الدراسة إلى تقييم دور التكنولوجيا الذكية في تطوير الميناء من خلال تحسين كفاءة الطاقة، وخفض الانبعاثات، وتعزيز الأداء التشغيلي. وقد أظهرت النتائج تحسنًا ملحوظًا بفضل تطبيق التطوير المستمر، بأنشاء رصيف متعدد الأغراض "تحيا مصر ١"، وتطبيق نظام Just-in-Time، واستخدام الطاقة الشمسية، والسيارات التى تعمل بالغاز الطبيعي. كما ساهم نظام النافذة الواحدة Port Single Window (PSW) في تبسيط الإجراءات وتعزيز الشفافية، في حين ساعدت المساحات الخضراء والإضاءة الشمسية في تقليل التلوث وتحسين جودة البيئة.

تؤكد هذه النتائج نجاح ميناء دمياط في التحول إلى نحو ميناء ذكي ومستدام، بما يدعم قدرته على جذب الاستثمارات ويعزز دوره الاقتصادي إقليميًا ودوليًا، رغم التحديات المحيطة.

الكلمات المفتاحية: الموانئ الذكية، ميناء دمياط، الاستدامة، تقليل الانبعاثات، اللوجستيات.

Abstract

Foreign trade is a fundamental element in bolstering national economies, with seaports playing a pivotal role in this domain, particularly in Egypt, which benefits from a strategic location connecting major global navigation routes. The Port of Damietta is a vital harbor contributing significantly to foreign trade flows, handling approximately 90% of Egyptian goods. However, it faces challenges related to energy consumption, emissions, and the efficiency of logistical operations.

This study aims to evaluate the role of smart technology in the port's development by enhancing energy efficiency, reducing emissions, and improving operational performance. The results demonstrate a notable improvement due to the implementation of continuous development initiatives, including the establishment of the multi-purpose "Tahya Misr 1" berth, the application of the Just-in-Time (JIT) system, the utilization of solar energy, and the adoption of natural gas-

powered vehicles. Furthermore, the Port Single Window (PSW) system has contributed to streamlining procedures and enhancing transparency, while green spaces and solar lighting have helped in mitigating pollution and improving environmental quality.

These findings underscore the success of the Port of Damietta in its transition towards a smart and sustainable port, which supports its capacity to attract investments and strengthens its economic role regionally and internationally, despite the surrounding challenges.

Keywords: Smart Ports, Port of Damietta, Sustainability, Emission Reduction, Logistics

1- Introduction

Ports play a crucial role in countries' national economy. As the main starting point for international trade through imports and exports, global waterways trade about 11 billion tons of goods annually, making them a vital element in strengthening the economic power of nations. Ports act as important sources of hard currency, encouraging the development of certain industries and contributing to the development of the surrounding areas. This great importance has resulted in increased regional and international competition, prompting countries to accelerate efforts to develop their ports (UNCTAD, 2023).

A recent study indicates that Egypt's distinctive geographical location makes it a central strategic point located at the intersection of the continents of Africa, Europe and Asia overlooking the Red Sea and the Mediterranean Sea associated with the Suez Canal. About12% of international shipping traffic crosses the Suez Canal," highlighting its vital importance in the global trade movement. This unique location has imposed on Egypt the need to develop its seaports to facilitate the passage of global trade and enhance its ability to counter competition with global ports (Damietta port authority, 2024).

The Egyptian Ministry of Transport carries out a comprehensive plan for the modernization and development of all elements of the transport system. This plan includes the improvement of transport means and networks, including roads and bridges, railways, tunnels, electric train, seaports, land and dry, logistics centers, as well as river transport. These efforts aim to meet the requirements of comprehensive development, to improve foreign trade services, promote transit trade and inland freight stations, and support tourism, industrial and commercial development. This trend aims to strengthen Egypt's position as a regional and global logistics center, thus prompting Egypt to invest in the development of its ports and enhance its competitiveness (Egyptian Ministry of transport, 2024).

Damietta Port is one of Egypt's leading seaports, its strategic location for Delta in the northeast of the Nile Delta, about 10 kilometers from the mouth of the Nile River on the Mediterranean to reach important agricultural and industrial areas in the Nile Delta and close to the main shipping routes, making it a major link between Mediterranean and Gulf markets, thereby strengthening its role as a vital logistic hub (Damietta port authority, 2024).

The port of Damietta has witnessed remarkable developments in recent years, adopting the latest technologies and mechanisms to improve its efficiency and enhance its competitiveness. One of the most important developments is the establishment of a multipurpose terminal to reduce waiting time, using the single window system, the FAL system has been activated and traded electronically on the port window. The tracksuit and departure forms were activated electronically (port development studies, 2024).

Automation systems are used to facilitate handling and storage, reduce the need for manual intervention and enhance the accuracy and speed of logistics operations (Rafaat, 2025).

As part of efforts to reduce greenhouse emissions and promote environmental sustainability the port of Damietta adopted strategies aimed at reducing the environmental impact of its operations. These strategies include the introduction of modern technologies to improve energy efficiency and reduce carbon emissions power supply, such as the delivery of electricity to ships on shore power supply and the obligation for ships to stop generators to reduce harmful emissions. Construction of 5 power plants using solar cells activation of the just in time system, conversion of approximately 11 cars to operate with natural gas clean energy equipment and advanced technologies to control ships' emissions and equipment. Waste management systems have also been developed more effectively, contributing to the preservation of the marine environment and enhancing the port's position as an example of environmental sustainability (environmental sustainability reports, 2024).

These developments are part of a comprehensive strategy aimed at improving the port's performance, enhancing its ability to meet the requirements of global trade and strengthening its role as a major logistics hub. Through these efforts, Port Damietta strives to strike a balance between economic growth and environmental conservation, enhancing its competitiveness and achieving sustainable benefits for the maritime transport industry (global port strategies, 2024).

2- Importance of the research

This research contributes significantly to demonstrating how smart technology and modern technologies mitigate environmental impacts, providing valuable guidance to other ports in their pursuit of the adoption and implementation of similar technologies. This in turn contributes to global efforts to improve the efficiency and sustainability of ports.

In addition, this research contributes to leading technological innovation by understanding the practical challenges and benefits associated with applying smart technology at Damietta Port. Research highlighted areas of technological improvement and innovation, proposing the latest developments in artificial intelligence that can enhance port efficiency and performance indicators.

The presentation of successful results from the implementation of smart technology can also enhance the attraction of domestic and foreign investments to Damietta port, as well as other ports seeking modernization. These results clarified the ability of smart technology to improve environmental and operational performance, making it a focus for investors and promoting development in the maritime sector.

3- Research Problem

Despite the vital role ports play in global trade and their environmental and technological impact, there is a lack of comprehensive understanding of how smart technology can improve energy efficiency and reduce emissions at some ports. Damietta Port adopts a range of smart technologies, but the challenge is to assess the effectiveness of these technologies in achieving their objectives of improving energy efficiency and reducing environmental impact. This research necessitates a thorough determination of the extent to which the implemented smart technologies have demonstrably improved energy utilization within the port's operations. Furthermore, it requires a robust assessment of the success of these technologies in measurably reducing emissions directly attributable to port activities.

4- Research Aim and Objectives

The research aims to explore the regional and global challenges facing Damietta Port in its efforts to become a smart port and identify opportunities for further improvement and investment.

Objectives:

1- Identification of smart technologies and marine innovations developed at Damietta Port

2- Assess the impact of smart technologies implemented at Damietta Port on energy efficiency, emission reduction and port performance.

3- Demonstrate the dual impact of these technologies on both environmental sustainability and economic performance and increased competitiveness.

5- Research Methodology

This research methodology relies on using a descriptive reviews approach by past literature and reports on smart technologies and digital transformation in seaports. This orientation helped build a knowledge base to understand the impact of these smart technologies in improving energy efficiency and reducing emissions. A case study focused on Damietta port development was then used, focusing on the port's smart technology to improve environmental and economic performance. The study reviews the impact of these applications on energy efficiency and emission reduction. Data collected through personal interviews of experts and academics in the management of ports and environmental technologies in Egyptian ports. The meta-audits were intended to assess the expected impact of new technologies on improving the port's operational and environmental performance. Using this integrated methodology, we were able to obtain comprehensive insights into the impact of smart technologies and digital transformation in improving energy efficiency and reducing emissions at Damietta Port.

6- Research Questions

1- Which specific smart technologies and innovations adopted at Damietta Port have had the most significant impact on improving energy efficiency and reducing emissions?

2- What regional and global challenges has Damietta Port faced in its efforts to become a smart port, and what opportunities exist for further enhancement and investment?

3- How can the advancements at Damietta Port serve as a model for similar initiatives in other Egyptian and regional ports, and what broader implications can be drawn for maritime logistics and environmental sustainability?

7- The Smart Port Concept

The concept of smart ports envisages transforming traditional ports into advanced and integrated systems where environmental impact, operational efficiency and energy consumption is carefully managed. The overarching goal is to develop ports into smart sustainable cities (SSC) within global supply chains. According to the International Telecommunication Union (ITU, 2015, p. 8), a sustainable smart city is defined as "an innovative city that uses information and communication technologies and other means to improve the quality of life, improve the efficiency of urban processes and services, and enhance competitiveness, while ensuring that the needs of current and future generations alike are met in economic, social and environmental terms".

Thus, if the port applies the requirements of the smart port, if some important indications are measured within the port such as the productivity and capacity consumed by ships, while waiting on the dock as well as the waiting time of ships on the dock, its impact for some indicators relating to the three dimensions of the sustainability supply chain, such as average wages for workers belonging to the social dimension of supply chain sustainability, the amount of emissions generated, the number of vessels that frequent the port, the length of their stay in the pier (environmental dimension), the sustainability supply chain and the world-wide arrangement of ports to demonstrate the efficiency of operations within the port, this "economic dimension" of supply chain sustainability (Heba, et al., 2019).

8- Smart Port Model

The Smart Port Model represents a comprehensive approach to transforming traditional seaports into highly efficient, technologically advanced, and environmentally sustainable hubs. This model integrates a variety of innovative technologies and strategies to optimize port operations and enhance their role within global supply chains. The core components of the Smart Port Model include (NASA MORE Conference, 2021).

Advanced Technological Integration:

- Incorporation of Internet of Things (IOT) devices, sensors, and data analytics to monitor and manage port activities in real time. This includes automated cargo handling, predictive maintenance, and enhanced safety measures.
- Sustainability Focus:
- Adoption of green technologies and practices aimed at reducing the environmental footprint. This involves utilizing renewable energy sources, implementing energy-efficient systems, and optimizing resource usage.

- **Operational Efficiency:**
- Streamlined processes through automation and digitalization to enhance throughput, reduce turnaround times, and improve overall efficiency. This encompasses the use of AI for logistics optimization, automated port equipment, and smart traffic management systems.
- Enhanced Connectivity:
- Development of robust communication infrastructure to ensure seamless integration with global supply chains and facilitate real-time information exchange among port stakeholders.
- Resilience and Adaptability:
- Designing infrastructure and systems to withstand and adapt to changing conditions, such as climate impacts or technological advancements. This includes resilient infrastructure and flexible operational strategies.
- Stakeholder Collaboration:
- Engaging various stakeholders, including port authorities, shipping companies, local communities, and technology providers, to align initiatives with broader economic, social, and environmental goals.

8-1 Characteristics of a Smart Port

A Smart Port is defined by several key characteristics that enhance its efficiency, sustainability, and overall functionality:

- Real-Time Data Monitoring: Continuous tracking of port operations through a network of sensors and data systems, providing actionable insights for decision-making and operational adjustments.
- Automation and Robotics: Use of automated systems for cargo handling, vessel traffic management, and port logistics to reduce human intervention and increase efficiency.
- Energy Efficiency: Implementation of energy-saving technologies and practices, such as electric or hybrid vehicles, energy-efficient lighting, and optimized energy consumption strategies.
- Environmental Stewardship: Measures to minimize environmental impact, including pollution control systems, waste management solutions, and initiatives to enhance air and water quality.
- Smart Infrastructure: Modernized port infrastructure designed to accommodate advanced technologies and support scalable and adaptable operations.
- Integrated IT Systems: Advanced IT solutions for managing port operations, including port community systems (PCS), and integrated logistics platforms that facilitate coordination among various stakeholders.
- Security and Safety Enhancements: Advanced security measures, including surveillance systems, cybersecurity protocols, and automated safety systems to protect assets and personnel.
- User-Centric Services: Services and facilities designed to enhance the experience for users, including improved customer service, user-friendly interfaces, and efficient processes for cargo handling and documentation (Basma et al.,2023)

9- Development at Damietta Port

The Port of Damietta Authority has launched a comprehensive development plan aimed at transforming the port into a smart sustainable port based on smart technology and emission reduction. This development included upgrading infrastructure and technology to enhance operational efficiency, environmental sustainability, and economic competitiveness (International Association of Ports and Harbors (IAPH), 2021).

The development strategy focused on introducing advanced technologies and improving operational processes, and integrating sustainability measures to meet the growing needs of global trade, details of the new techniques implemented are as follows:

9-1 "Tahya Masr 1" multi-purpose container terminal

The multipurpose container terminal at Damietta Port is one of the most prominent infrastructure projects aimed at enhancing the port's capabilities in dealing with the movement of containers and miscellaneous goods. The terminal runs 681 meters, 17 meters deep, enabling it to accommodate large vessels and greatly enhance the port's operational capability. The objective of the container terminal is:

Increased capacity: The terminal provides the ability to handle a larger volume of containers and miscellaneous goods, enhancing Damietta Port's ability to meet global and domestic trade needs more efficiently.

Reduce waiting time: The dock design enables large depth of ships to dock without delay, reducing the waiting time of ships and enhancing the speed of handling operations.

Improved operational efficiency: the terminal provides state-of-the-art port equipment such as cranes and advanced logistics tools, which contributes to improving the speed and efficiency of container loading, unloading and intelligent tracking operations to enhance the accuracy and efficiency of port operations.

Reducing emissions: By reducing ship waiting time and enhancing fast handling operations, the terminal contributes to reducing emissions from the operation of ship generators during the waiting period. This is in line with recent environmental trends in reducing adverse impacts on the environment, improved logistical performance: the terminal contributes to improved cargo flow and reduced congestion at the port, enhanced efficiency of logistics operations and helped facilitate trade movement (European Commission, 2022).

Modern infrastructure: The terminal features a design that conforms to the latest global infrastructure standards, including docks capable of accommodating the latest types of ships, and modern navigation techniques.

Tahya Misr Container Terminal (l) Multipurpose Port Damietta Authority is an important step towards development.

9-2 Activation of Just in Time system at Damietta Port

The Port Authority of Damietta is improving the efficiency of port operations and mitigating environmental impacts through the application of the "Just in Time" (JIT) system, which relies on ship tracking techniques such as global positioning system (GPS) and marine traffic management systems or Vessel Traffic Services (VTS): -

These techniques allow accurate monitoring of ships' movement and analysis of their data, helping to accurately predict their arrival dates and coordinate their arrival timings to avoid congestion at the port. By improving arrival timings and reducing ship staying time in the waiting area, the need to operate ship generators is reduced, reducing fuel consumption and emissions of harmful pollutants, contributing to improved air quality and reduced environmental impacts. Through this strategy, Damietta Port enhances its operational efficiency and achieves higher environmental sustainability (Damietta Port Authority, 2024).

9-2-1 Types of VTS:

- Port VTS: These are localized systems within ports or harbors to manage vessels arriving at or departing from the port, ensuring safe docking, loading, and unloading processes.
- Coastal VTS: Used along busy coastal areas to monitor and manage the flow of vessels along major shipping routes, preventing accidents and improving safety for ships navigating near shorelines.
- River and Inland VTS: Implemented on rivers and inland waterways to monitor and control vessel traffic in areas that are often narrower and more complex than coastal waters, ensuring safe passage for all types of vessels.
- Area VTS: Covering a broader maritime area, these systems are used to manage vessel movements in congested regions that span large geographical areas, like busy straits or sea lanes (Terry Hughes et al.,2019)

9-2-2 Marine Traffic Management System:

Vessel tracking: Global positioning technologies and maritime traffic management systems are used to monitor and analyses ships' traffic. This allows accurate forecasting of ships' arrival dates and coordinated arrival dates so that they arrive on time to avoid congestion.

Data Analysis: Through cooperation with shipping and joint planning companies, ship arrival schedules are improved based on loading and unloading schedules. Data analysis is also used to improve handling timing and reduce unnecessary downtime.

Automation Systems: Technologies used in JIT include advanced automation systems in container loading and unloading processes, which accelerates procedures and reduces human errors.

Emission reduction: Reducing generator operation means reducing vessel waiting time and reducing the need to operate generators freely, resulting in lower fuel consumption and reducing harmful emissions such as nitrogen oxides and sulfates, the number of pollutants emitted into the air from generators is reduced, contributing to improved air quality in the port area.

9-3 Onshore Power Supply (OPS):

An integrated infrastructure for supplying ships with electricity from land. OPS has been developed, reducing the need to operate ship generators and reducing harmful emissions in accordance with annex VI of the MARBOL Convention 73/78 which aims to reduce air pollution from ships where the system obliges ships to decommissioning their generators while in port in compliance with international environmental standards.

This system reduces the emissions of nitrogen oxides and sulfates, which contributes to the improvement of air quality in the port area, advanced electric charging stations have been installed in the port docks to supply ships with electricity while they are present, requiring appropriate infrastructure such as high voltage cables and electrical transformers.

The system includes intelligent energy management to ensure the balance of load and energy saving in an efficient and sustainable manner, as well as the development of customized delivery components that conform to the specifications of different vessels to ensure the smooth and safe supply of electricity to ships.

Using measurement and surveillance technology to track energy consumption and record data needed to ensure optimal operation of the system, using clean and renewable sources of energy to generate electricity supplied to ships, such as solar or wind energy, thereby enhancing the port's environmental sustainability, as well as developing advanced cooling and heating systems to help ships maintain appropriate operating conditions during road power connections(International Maritime Organization (IMO), 2020).

9-3-1 Training and rehabilitation of the crew

Ships and crew should be provided with training program on how to properly use OPS to ensure compatibility with environmental requirements, and enhance awareness among operators on the importance of adhering to OPS requirements and environmental impacts of generator operation, as it contributes to reducing fossil fuel vessels, significantly reducing energy consumption and improve the port's energy efficiency.

9-4 Construction of five solar power plants at Damietta port

As part of Damietta Port's strategy to promote environmental sustainability and reduce environmental impacts, an important step has been taken with the establishment of five solar power plants. This project aims to reduce dependence on traditional energy sources such as fossil fuels, which contribute to the consumption of natural resources and release of harmful pollutants. Solar panels will be installed in strategic locations across the port, which will contribute to reducing fuel consumption and reducing harmful emissions such as nitrogen oxides and sulfate. This shift to solar not only enhances energy efficiency but also contributes to improved air quality in the port area and achieves environmental goals for sustainable development (IRENA, 2021).

9-5 Conversion of cars to operate natural gas to reduce emissions

As part of the development and work to reduce greenhouse gas emissions, emphasis is placed on converting a number of cars into Damietta Port to operate with natural gas rather than conventional fuel, through this conversion, significant reductions in harmful emissions are expected, contributing to improved air quality and reducing the environmental impact of the port's activities (Damietta Port Authority, 2024).

9-6 Application of single port window system (PSW)

The only port window - PSW is a regulatory and technical framework aimed at streamlining and standardizing procedures to deal with various stakeholders inside and outside the port, facilitating the flow of information and reducing bureaucracy. This system allows customers to send all required documents and information through one platform, improve efficiency and reduce time and costs associated with the procedures, PSW has many standards including: -

Data Integration: Through a unified and centralized platform, all documents and information related to port operations, such as customs licenses, shipping data and vessel information, can be provided and managed.

The system also coordinates with various systems, such as the Marine Traffic Management System and the Financial System, providing an integrated and smooth customer experience, and by standardizing order and information processing processes, PSW reduces the need to deal with several different destinations, saving time and effort and contributing to accelerated removal and approval procedures, improving the speed of ship and cargo flow within the port (UNCTAD, 2021).

Enhancing transparency: The system provides a mechanism for tracking the status of requests and transactions in a transparent manner, facilitating verification of procedures and enhancing transparency. Documents and approvals are exchanged electronically, reducing the use of paper and the speed of procedures.

Through the application of the single port window system, Port Damietta seeks to improve operational efficiency and simplify procedures, enhance performance effectiveness and achieve a better customer experience, to keep pace with the development globally and locally within the ports of the Arab Republic of Egypt.

10-Energy efficiency and emission reduction measures in Damietta Port

Environmental pollution management at Damietta Port is an essential part of the port's sustainable development strategies, which aim to balance operational efficiency and environmental protection. Port management seeks to develop environmental mechanisms that reduce negative impacts and support sustainability by addressing dust, light, noise and waste pollution. Strategies also include the promotion of green spaces, reflecting a deep commitment to preserving environmental quality and enhancing the port's role as a major trading and shipping hub in the region (Damietta Port Authority, 2024).

Increasing Green Spaces: Damietta Port expands its green space, a procedure aimed at reducing dust pollution. These spaces contribute to improving air quality and reducing the effects of dust on the environment and people's health.

Solid waste management: Solid waste is collected from ships and other activities at the port in specific areas to ensure proper disposal and keep the environment clean. This waste is transported to the Farascore dump, where it is processed in accordance with approved waste management practices. In addition, hazardous wastes are delivered to Public Environmental Protection Authority -accredited contractors with environmental licenses required to handle such wastes.

Solar Lighting System: A solar-powered lighting system has been applied in the port, significantly reducing light pollution. The initiative supports the use of renewable energy sources and mitigates the environmental impact associated with traditional lighting systems.

Monitoring noise levels: Decibel measurements are used to monitor noise levels within the port, ensuring compliance with established legal limits. This strategy requires port companies to conduct environmental assessments of noise from their equipment, as well as periodic maintenance to ensure compliance with international standards.

11- Regional and global challenges for Damietta Port

Damietta's efforts to become a smart port face several regional and global challenges, including:

- Adaptation to global environmental standards, financial pressures to finance new technologies and economic volatility affecting infrastructure investments. Advances in smart technologies also require appropriate technical skills and training for employees.
- Investing in sustainable technologies: Damietta Port can benefit from investing in new technology such as artificial intelligence and dual cohesion to predict and address any challenges facing the port by proactively developing technical solutions to improve logistics and cope with crises.
- The port can seek funding from green project investment funds or international grants to support sustainability projects.

12- Results

The development of the port of Damietta has shown several positive results that reflect the effectiveness of the strategies implemented to enhance operational efficiency and environmental sustainability. The establishment of the multi-purpose terminal "Tahya Egypt 1" at the port of Damietta has greatly enhanced the port's capacity and efficiency, enabled faster handling of containers and reduced waiting times for ships. Advanced equipment and logistics tools improved container loading, unloading and tracking, reducing congestion. The environmental impact has been reduced by the implementation of Just in Time (JIT), reducing fuel consumption and harmful emissions, along with the Earth power supply system and renewable energy sources such as solar energy. In addition, the transition to natural gas-powered vehicles has reduced emissions. The introduction of the Single Window System (PSW) has streamlined processes, reduced bureaucracy, enhanced transparency, improved operational efficiency and customer experience.

The expansion of green spaces in Damietta port improved air quality by reducing dust pollution, benefiting public health. The solar-powered lighting system has reduced light pollution and supported the use of renewable energy. These efforts reflect the port's commitment to enhancing operational performance while prioritizing environmental sustainability and a successful balance between economic growth and environmental stewardship.

Consequently, it can be asserted that the three dimensions of sustainability are being achieved through the application of smart sustainable port requirements. The environmental dimension is addressed via innovative technologies that reduce emissions and increase energy efficiency, while the social dimension contributes to the improvement of working conditions and social equity by providing a safer and more sustainable working environment. The economic dimension is realized through enhanced operational efficiency and increased port competitiveness, which contributes to long-term sustainable economic growth.

13- Conclusion

Damietta Port's comprehensive development plan represents significant progress towards transforming it into a smart and sustainable port. Through strategic improvements and integration of advanced technologies, the port aims to enhance its operational efficiency, environmental sustainability and economic competitiveness. Key initiatives such as the "Tahya Egypt 1" multipurpose container plant, the operationalization of Just in Time (JIT), the implementation of the onshore power supply (OPS), and the construction of solar power plants are pivotal in achieving these objectives.

The development of green spaces, the transition to natural gas, and the application of the single port window system further confirms the port's dedication to reducing environmental impacts and enhancing operational effectiveness.

The Port of Damietta's development efforts are aimed not only at meeting the growing demands of world trade, but also at setting a standard for port sustainability and efficiency. Sustained investment in innovative technologies and the introduction of artificial intelligence and sustainable practices will be critical in maintaining the port's competitive advantage and contributing positively to local and global environmental goals. Through these initiatives, Damietta Port is preparing to strengthen its role as a major trading and shipping hub, demonstrating a proactive approach to addressing environmental challenges and promoting sustainable development.

14- Recommendations

Assessing the long-term impact Future research should focus on long-term assessments of the impact of smart port initiatives in Damietta Port. This could include a detailed analysis of the ongoing environmental benefits, operational efficiencies and economic impacts of technologies implemented over a long period.

1- To study a comparison between Damietta Port and other smart ports globally, by examining many smart port applications, researchers can identify best practices, common challenges and innovative solutions that can enhance Damietta Port strategies.

2- Stakeholder engagement: Further research should be undertaken to explore the role of stakeholder engagement in the successful implementation of smart port initiatives. Understanding the views and participation of various stakeholders, including communities, port authorities and technology providers, can help maximize cooperation and address potential challenges.

3- Investigating the impact of emerging technologies, such as advanced AI algorithms, supply chain management blockchain and next-generation renewable energy solutions, on smart port operations can provide new ways to enhance port efficiency and sustainability.
4- Economic impact studies to assess financial benefits and cost-effectiveness of smart port investments, including investment return and economic impact analyses, can guide future investments and policy decisions.
5- Study climate resilience, which focuses on the climate resilience of smart ports, to take proactive action in the face of extreme weather events and sea level rise.

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