ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΕΙΡΑΙΩΣ

UNIVERSITY OF PIRAEUS

DEPARTMENT OF MARITIME STUDIES

SCHOOL OF MARITIME AND INDUSTRIAL STUDIES

MSc IN SHIPPING MANAGEMENT

FUEL CONSUMPTION AND WEATHER ROUTING WITH THE USE OF ARTIFICIAL INTELLIGENCE

RAFALIAS ARISTEIDIS

Master-Thesis

submitted to the Department of Maritime Studies of the University of Piraeus to cover the requirements for the completion of the MSc in Shipping Management graduate program

Piraeus

November 2024

The person who carries out the thesis bears the entire responsibility of determining the fair use of material, which is defined on the basis of the following factors of the purpose and character of the use (commercial, non-profit or educational), the nature of the material used (extract, part of text, drafts, figures, images or maps), the proportion and importance of the part it uses in relation to the whole copyrighted text and the possible consequences of such use on the market or the general value of the copyrighted text.

The present Master Thesis was approved by the Three-Member Examination Committee appointed by the General Assembly of the Department of Maritime Studies, University of Piraeus, in accordance with the Operating Regulations of the Postgraduate Program in Maritime Administration.

The Committee's members were as follows:

- Alexander Artikis (Supervisor)
- Ioannis Lagoudis
- Dionisios Polemis

The approval of the Thesis by the University of Piraeus Department of Maritime Studies does not imply acceptance of the author's opinions.

Thank you,

Andreas Kouvaras

Table of Contents

Abstract

This thesis explores how artificial intelligence (AI) can be used to solve two important problems facing the maritime sector: maximising fuel efficiency and putting effective weather routing into practice. The shipping sector, a vital component of international trade, is coming under growing pressure to lessen its environmental impact without sacrificing operational effectiveness. This study investigates the revolutionary potential of AI-driven approaches in accomplishing these objectives.

The study starts by placing the economic and environmental issues facing the shipping sector in context and highlighting how urgent it is to comply with global laws like the Energy Efficiency Operational Index (EEOI) and the IMO 2050 agenda. These frameworks emphasise how important it is to implement creative ways to reduce greenhouse gas emissions and improve energy efficiency.

The technical foundation of this thesis is a comparison of two prediction techniques: Deep Neural Networks (DNN) and the Simplified Naval Architecture Method (SNAM). While SNAM provides a simple approach to fuel consumption estimation based on environmental parameters and vessel design, DNN uses complicated, nonlinear data interactions to achieve greater forecast accuracy. While more work is required for containerships, the analysis shows that DNN is advantageous in situations involving bulk carriers and oil tankers.

The study also looks at how AI is being incorporated into weather routing, demonstrating how it can evaluate real-time weather data to create the best routes that save fuel and improve safety. Case studies demonstrate observable advantages in fuel economy, cost reduction, and environmental compliance, including AI-based technologies like OptiNav and Sofar Pathfinder.

In the end, this study highlights AI's potential to completely transform the marine sector by providing workable solutions for sustainability and legal compliance. The results support the wider use of AI technologies to promote environmental responsibility and efficiency in international shipping.

CHAPTER 1: THE IMPORTANCE OF SEA TRADING AND THE ENVIRONMENTAL IMPACT

1.1Introduction

The international shipping sector facilitates the transportation of commodities across oceans and links global marketplaces, acting as the backbone of global trade. This industry serves a crucial part in the movement of raw materials, finished products, and energy resources, which is essential for driving economic growth and development. It consists of a large network of ships, ports, and logistical systems. Maritime transport is responsible for around 90% of global trade, underscoring its importance in the worldwide supply chain. The global shipping business, being dynamic and complex, has various problems such as environmental restrictions, technology improvements, security risks, and economic volatility. Notwithstanding these obstacles, it persists in developing new ideas and adapting, aiming for improved effectiveness, security, and environmental friendliness to fulfil the requirements of an increasingly interconnected globe (Donepudi,2014).

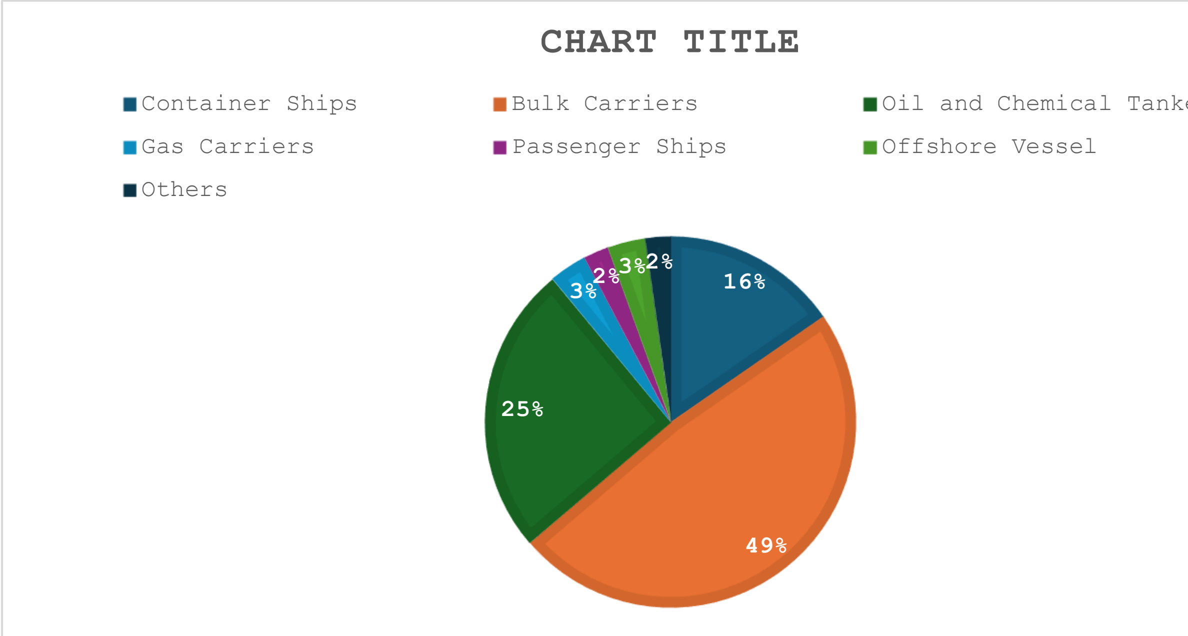
Maersk, MSC (Mediterranean Shipping Company), COSCO, CMA CGM, and Hapag-Lloyd are among the largest global shipping corporations (Anwar,2020). Their fleet comprises container ships, which are utilized for transporting standardized shipping containers and serve as the fundamental support of the shipping sector. Additionally, they possess Bulk Carriers, which are employed for transporting bulk commodities such as coal, grain, and ores. Conversely, tankers are used to transport liquid cargo, such as oil and various chemicals. Lastly, we have general cargo ships that transport a diverse range of items that cannot be carried using containers or bulk carriers.

The sea has served as a longstanding commerce route, having an indissoluble history and significance in our environment since prehistoric times. The Greek islands in the Aegean Sea and Mediterranean coast have historically been a hub of vibrant trade, bringing prosperity to the local population (Cartwright, 2020). Numerous archaeological discoveries have preserved evidence of the riches that were exchanged throughout the ages. Despite technological advancements and adaptations in transportation modalities, including trains, highways, and airplanes, the ocean continues to be the preferred mode of moving large quantities of cargo through commercial ports. Documentation and administrative tasks continue to be crucial components of exchange networks, with loading and unloading ports playing a particularly vital role in their functionality. Although the industry has undergone modernization, there are still numerous hazards that pose concerns to the safety and well-being of workers (Conroy, 2019). The dangers encompassed in this context comprise of inadequate loading or assembly, things falling, harm caused by external leaks, and unsuitable working conditions on docks. Because of all the above reasons, a short yet meaningful method has been constructed to address the numerous hazards encountered by workers in ports. Maritime transportation is of utmost importance in worldwide trade and business[3].

Here are some key points to consider about shipping (Forwarder Magazine, 2020):

1. **Essential for Global Trade**: Maritime transportation serves as the fundamental backbone of international commerce, enabling the transit of goods across countries and continents. It enables cost-effective transportation of large volumes of commodities in comparison to alternative forms of transportation.
2. **Cost-Effectiveness**: Sea shipping is typically more economically efficient than alternative transportation methods, such as air cargo or land transit. Cost efficiency is particularly crucial for large-scale cargo and shipments that are not time-sensitive. As an example, the shipping expense for a 500-kilogram (1100-pound) cargo can be $195 if it is transported by sea. Alternatively, the identical product will incur a cost of $1,000 if it is transported by airplane (Max Baehr, 2022)
3. **Accessibility to Remote Areas**: Sea travel offers the opportunity to reach rural and inland areas that are not readily accessible through alternative methods. Ports serve as crucial access points that link these regions to international markets.
4. **Economic growth**: Ports and maritime infrastructure play a crucial role in stimulating economic growth and promoting development. They generate employment opportunities, entice capital inflow, and invigorate regional economies through the facilitation of trade and commerce.
5. **Environmental Impact**: Sea transport, while generally more fuel-efficient and emit less CO_2 per tonne of cargo than other modes of transport, still contributes to pollution primarily through the release of sulphur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter. The type of the fuel that the ships are using (Heavy Fuel Oil) and the type of their engines (Slow Steaming) are some of the reasons of the high CO_2 emit to the environment. Attempts are being undertaken to mitigate these environmental effects by employing cleaner fuels, technical advancements, and regulatory interventions.

Figure 1: CO_2 emissions by ship type in 2020 [Unit: million metric ton].



Source: Sang-Su, 2024

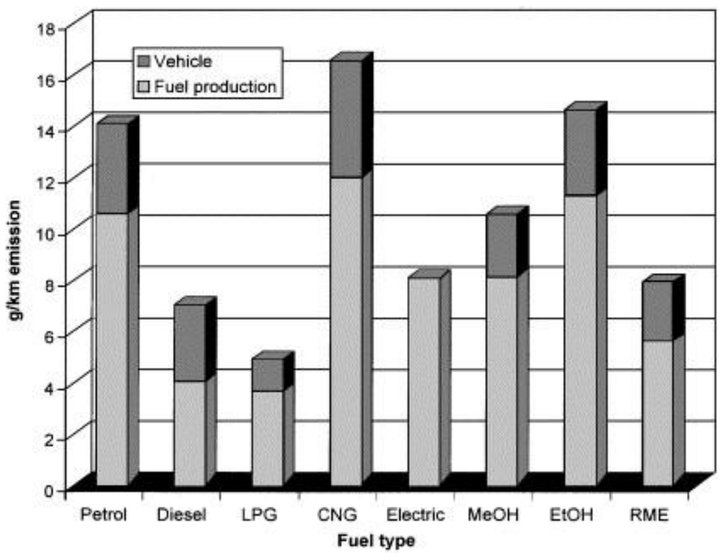
6. **Challenges and Risks:** Shipping encounters several problems and threats, such as piracy, natural disasters, geopolitical conflicts, and law enforcement issues. Nevertheless, progress in technology, transportation infrastructure, and safety protocols is aiding in the mitigation of these hazards.

Nevertheless, progress in technology, transportation infrastructure, and safety protocols is aiding in the mitigation of these hazards.

1.2 Environmental Impact and Global Shipping

The continuous expansion of global trade is increasing the number of all kind of vessels, resulting in hazardous emissions that worsen the problem of greenhouse effect. These ships significantly contribute to the increased emissions of carbon dioxide[4]. The global shipping industry is a significant contributor to air pollution as it heavily depends on the use of heavy fuel oil, which is a highly polluting form of fossil fuel. Maritime shipping contributes to around 2-3% of worldwide carbon dioxide (CO2) emissions. Figure 2 shows us the life cycle of hydrocarbon emissions during it's evaporation process even if the engine or the vehicle is not in use.

Figure 2: Life-cycle hydrocarbon emissions including methane for light goods vehicles as a function of fuel type.



Source: R.N Colvile, 2001

Several regulatory groups, such as the International Maritime Organisation (IMO), have established objectives and implemented strategies to decrease the ecological impact of shipping. However, those endeavors seem inadequate to address the issues associated with the shipping zone because not all shipowners have adjusted them to their ships. Currently, the greenhouse effect is one of the most significant environmental challenges we are encountering. Greenhouse gases are a group of gases present in the biosphere that trap heat and cause an increase in the planet's temperature. The primary greenhouse gases comprise carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), and certain chlorofluorocarbons (CFCs).

Shipping significantly adds to the emissions of greenhouse gases. The key components of emissions from shipping are ship gas combustion, the utilisation of natural petrol as fuel, as well as emissions from petrol storage and transportation.

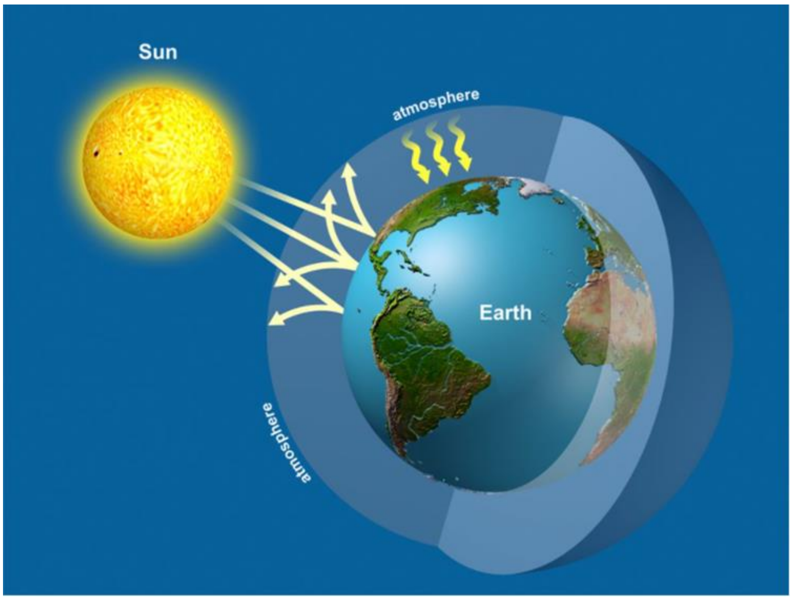
These emissions provide a substantial contribution to the increase in CO2 and other greenhouse gases in the environment, worsening the greenhouse effect and climate change. The consequences of those modifications include the increase in global temperatures, alterations in climate patterns, sea level elevation, loss of natural resources, and reduction in biodiversity.

In order to mitigate this inconvenience, it is necessary to implement measures aimed at reducing emissions from delivery processes. These steps may also include the utilisation of cleaner fuels such as LNG or biofuels, the implementation of emission reduction systems on ships, and the promotion of environmental awareness throughout the maritime industry. By adopting this approach, we will mitigate the adverse effects of transport on the environment and make a significant contribution to reducing the greenhouse effect (Christopoulos, et al, 2014).

The greenhouse effect is an inherent natural phenomenon that occurs without any human interference. It is a vital mechanism that is essential for the Earth to sustain life, as without it, the planet would be uninhabitable. The concept was initially identified by Joseph Fourier, a French mathematician, physicist, and astronomer, in 1838. It was subsequently expanded upon by Svante Arrhenius, a Swedish chemist. Arrhenius formulated the hypothesis that the release of carbon and other pollutants into the atmosphere by human industrial activities will result in significant repercussions on climate change (Arrhenius, 1896).

The greenhouse effect refers to the increase in Earth's average temperature. The Earth receives substantial amounts of solar radiation at the boundary of its atmosphere, with a portion being absorbed and the remainder escaping into space. Around 30% of the incoming radiation is reflected, with 6% passing through the biosphere, 20% passing through clouds, and 4% being absorbed by the Earth's surface. The biosphere absorbs 16% of solar energy, whereas clouds absorb 3% and the surface and oceans absorb 51%. This phenomenon, known as the greenhouse effect, is crucial for creating habitable conditions on Earth. Without it, the average temperature would plummet to approximately -18°C.

Figure 3: Global Warming



Source: EE & Europe Climate Pact, 2022

Greenhouse gases (GHGs) are gases present in the Earth's biosphere that have the ability to trap heat, hence enhancing the greenhouse effect and leading to global warming. Figure 3 presents how global warming happens. These gases absorb and release radiation in the thermal infrared range, increasing in the temperature of the Earth's surface and lower atmosphere. Below are several prominent greenhouse gases and their respective sources of emissions:

- **Carbon Dioxide** (CO_2) is the predominant greenhouse gas released as a result of human activity. Typically, it is generated by burning fossil fuels such as coal, oil, and natural gas for purposes such as generating energy, transportation, commercial activities, and deforestation.
- **Methane (CH_4):** Methane is a potent greenhouse gas that has a far higher ability to trap heat compared to CO_2 over shorter periods of time. Methane is released from natural sources such as wetlands, as well as from human activities including cattle rearing, rice cultivation, landfills, and the extraction and distribution of fossil fuels.
- **Nitrous Oxide** (N_2O) is released into the atmosphere as a result of agricultural practices, commercial operations, and the burning of fossil fuels. It is also emitted by botanical sources, such as soil and oceans. Nitrous oxide exerts a significant influence on climate change and contributes to both the phenomenon of global warming and the loss of the ozone layer.

- **Fluorinated gases**, such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF6), are man-made gases used in various industrial applications, including refrigeration, air conditioning, and electronics production. These gases possess a significantly high global warming potential and can endure in the environment for an extended period.
- **Water vapour**, the most prevalent greenhouse gas in the atmosphere, is primarily influenced by temperature fluctuations and natural processes. Human activities indirectly impact water vapour levels by altering atmospheric conditions, such as through deforestation and changes in land use.

The three crucial greenhouse gases that we need to focus on are Carbon Dioxide, Methane, and Nitrous Oxide. The release of these greenhouse gases contributes to the greenhouse effect, leading to global warming and climate change. Efforts to reduce greenhouse gas emissions involve shifting to renewable energy sources, enhancing electricity efficiency, adopting carbon capture and storage technologies, advocating for sustainable land management practices, and reducing emissions from commercial activities and transportation. Furthermore, international accords such as the Paris Agreement aim to collaboratively decrease the release of greenhouse gases in order to restrict the global increase in temperature and alleviate the consequences of climate change (IMO,2020).

Table 1 is being developed based on research conducted by the Intergovernmental Panel on Climate Change using data from 1750 to 1998 and shows the increase of various greenhouse gasses during that time.

Table 1: Crucial greenhouse gases

Greenhouse Gas	1750 values	1998 values	Increase (%)	Influence on Global Warming [W/m2]
CO2	87 ppm	365 ppm	31%	1,46
CH4	1045 ppb	1745 ppb	150%	0,48
N2O	44 ppb	314 ppb	16%	0,15

Source: Intergovernmental Panel

1.3 International Maritime Organization's actions on Global Warming

The maritime Maritime Organisation (IMO) is a specialised organisation of the United Nations that has the authority to regulate and oversee maritime shipping. The International Maritime Organisation (IMO), founded in 1948, is headquartered in London, United Kingdom. It functions as the worldwide authority for establishing standards related to the safety, security, and environmental impact of international shipping.

The IMO's jurisdiction is extensive and covers a wide range of marine matters, including:

1. **Safety of Navigation** The International Maritime Organisation establishes regulations and standards to prevent accidents that result in loss of life or property, ensuring safety of navigation at sea. One of its additional functions is to provide specifications for ship construction, including the materials to be used. It also determines the navigational aids that should be available and the crew management procedures that may be implemented to govern movement.
2. **Prevention of Pollution:** The main objective of the IMO is to prevent and decrease maritime pollution caused by ships. This includes addressing pollution from oil spills and harmful emissions, such as chemical flotation agents, in both water and air. The marine organisation establishes regulations and directives that require ships to comply with specific criteria to prevent pollution. Additionally, it provides ideas on how to mitigate the environmental impact of such transportation.
3. **Security of Shipping:** The International Maritime Organisation (IMO) implements regulations and tactics to enhance security measures in ports and aboard ships, with the aim of preventing hijacking, terrorist acts, and theft at sea. One significant example is the International Ship and Port Facility Security (ISPS) Code, which establishes varying security requirements for different boats operating in different regions of the world.
4. **Legal Framework:** The IMO plays a role in creating a standardised method of collaboration in maritime affairs between countries worldwide by simplifying the implementation of international treaties and agreements. These include various agreements such as the International Convention for the Safety of Life at Sea (SOLAS), the International Convention for the Prevention of Pollution from Ships (MARPOL), and the International Convention on Standards for Training, Certification and Watchkeeping (STCW) for Seafarers, among others.

5. **Technical Cooperation:** The IMO supports its members, particularly developing countries, by offering technical assistance and capacity building to help them comply with international. This encompasses training programmes, seminars, and projects that specifically aim to enhance maritime safety, security, and environmental protection.

IMO plays a crucial role in promoting safe, secure, and ecologically responsible global marine activity to improve international trade, the economy, and sustainable development. IMO encompasses a wide range of regulations that cover various aspects such as maritime safety, accident prevention at sea, emissions of greenhouse gases (GHGs) from ships and other substances that emit greenhouse gases, waste management policies for vessels, and the conservation of marine species and the environment. The International Maritime Organization (IMO) comprises 174 participants, including United Nations member states as well as other relevant international organizations and non-governmental organizations (NGOs) involved in the shipping industry. The International Maritime Organization (IMO) has an administrative council, often known as the Maritime Council, along with other subsidiary groups and committees that oversee various elements of shipping. The International Maritime Organization (IMO) facilitates the process of delivering goods by promoting marine safety and security, ensuring that member states adhere to international regulations, and fostering innovation and sustainability within the industry.

The IMO plays a significant role in improving the quality and safety of global maritime transportation due to its international influence. The Paris Agreement, often known as the Paris Climate Agreement, is a global treaty agreed on December 12, 2015, in Paris, France, during the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC). The settlement is a significant achievement in the worldwide struggle to tackle climate change. The primary objectives of the Paris Agreement are to limit the global temperature increase to below 2 degrees Celsius compared to pre-industrial levels and to strive for a limit of 1.5 degrees Celsius, with the purpose of mitigating the effects of climate change. The agreement includes enforceable targets for member countries to reduce greenhouse gas emissions, as well as steps to adapt to and mitigate the impacts of climate change. Furthermore, it offers methods to facilitate the funding and technology transition for economically disadvantaged nations. The Paris Agreement has been universally accepted and functions as a crucial instrument for addressing and mitigating greenhouse gas emissions, to minimize the effects of climate change on a global level (The economist, 2015).

1.3.1 IMO 2050 strategy

The IMO 2050 strategy pertains to the International Maritime Organization's (IMO) inclusive blueprint aimed at mitigating global shipping's greenhouse gas (GHG) emissions. Implemented in April 2018, this approach seeks to synchronise the maritime area with the overarching goals of the Paris Agreement, which aim to limit global warming to less than 2 degrees Celsius above pre-industrial levels and strive to limit temperature increase to 1.5 degrees Celsius (IMO,2018).

The IMO 2050 concept encompasses several crucial components:

1. Greenhouse Gas (GHG) Reduction Targets: The approach aims to significantly reduce greenhouse gas (GHG) emissions from international shipping. Specifically, the goal is to reduce the overall greenhouse gas (GHG) emissions from shipping by at least 50% in 2050 compared to the levels recorded in 2008, with the ultimate aim of completely eliminating them.
2. The International Maritime Organisation (IMO) has set a goal to reduce the carbon intensity of worldwide shipping by 2050, in addition to reducing overall emissions. This entails reducing greenhouse gas (GHG) emissions per unit of transport effort, such as metric tonnes per kilometre of cargo transported.
3. The primary emphasis is on the significance of research and development (R&D) in the creation and application of novel technologies and fuels with the objective of achieving the emission reduction targets. These initiatives encompass supporting the production of zero-carbon fuel, promoting processes that drive energy conservation, and advancing energy-saving technologies.
4. In its 2050 strategy, the International Maritime Organisation (IMO) acknowledges that market-based measures (MBMs) could be crucial in attaining the objectives of reducing emissions. These strategies may include implementing carbon pricing mechanisms or emissions trading schemes with the goal of reducing emissions in the shipbuilding industry.

5. International cooperation is crucial for the successful implementation of the IMO 2050 strategy, given the global nature of maritime trade and emissions. To promote the adoption of an eco-friendly, low-carbon maritime transport system among member states, it is essential for stakeholders and international organisations worldwide to collaborate in accordance with the guidelines of the International Maritime Organisation (IMO).

The IMO 2050 strategy is a significant advancement in the shipping industry, since it contributes to the mitigation of global warming and the preservation of the environment. It is a tool designed to facilitate coordinated efforts to decrease the amounts of carbon emissions from ships globally, as part of comprehensive steps to combat global climate change. The regulations described below aim to identify the strategy that originated from these principles (Parker,2022):

- **EEDI (Energy Efficiency Design Index)**:
  - Seeks to encourage the utilisation of ship designs that are energy-efficient.
  - Establishes precise energy efficiency standards for newly constructed vessels, taking into account their dimensions and classification.
  - Implemented with the aim of mitigating the release of greenhouse gases from ships by enhancing their energy efficiency.
- **EEXI (Energy Efficiency Existing Ship Index)**:
  - This policy is applicable to already existing ships and has the objective of enhancing their energy efficiency.
  - Establishes criteria for current vessels to comply with designated energy efficiency benchmarks.
  - Assists in decreasing the release of greenhouse gases from the current group of ships by enhancing and streamlining ship operations
- **SEEMP (Ship Energy Efficiency Management Plan)**:
  - Mandates the creation and execution of a Ship Energy Efficiency Management Plan for ships.
  - Intended to assist ship owners and operators in enhancing the energy efficiency of their vessels by implementing operational measures.

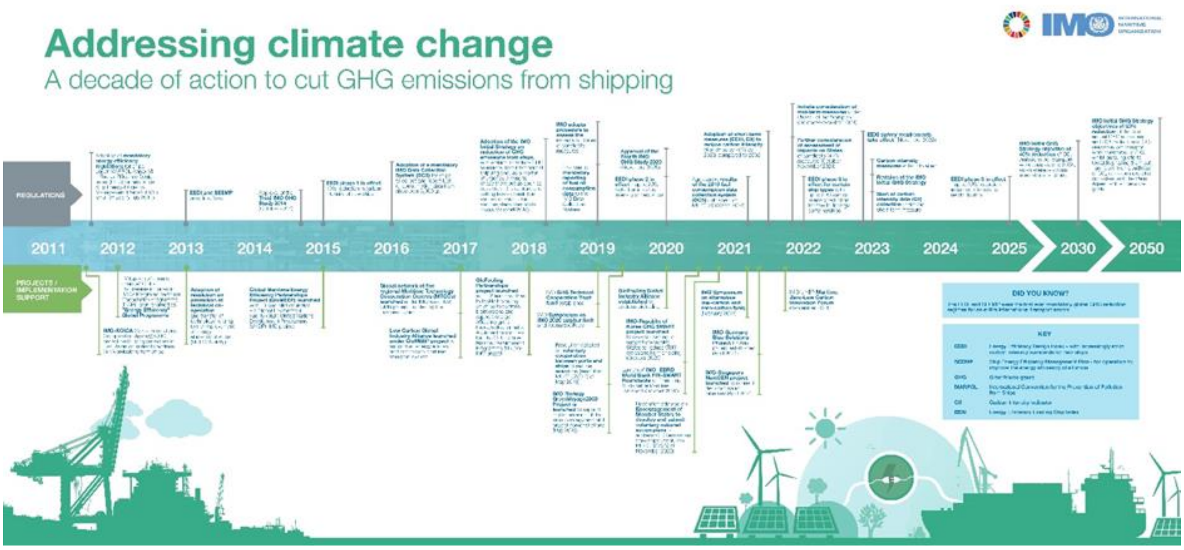
- Implements strategies such as enhancing velocity, designing efficient routes, cleaning the ship's exterior, and maintaining the propeller to decrease fuel usage and emissions.

- **DCS (Data Collection System)**:
    - Ships exceeding a specified length are required to collect and document data on fuel use, distance covered, and other pertinent factors.
    - Seeks to enhance clarity and streamline the process of tracking the amount of fuel used and pollutants emitted by ships.
    - Offers valuable data for evaluating the efficacy of energy efficiency initiatives and guiding future policy decisions.

- **CII (Carbon Intensity Indicator)**:
    - Proposed regulation to establish a Carbon Intensity Indicator for ships.
    - Intended to measure a ship's carbon emissions relative to its transport work (e.g., tonne-mile).

A standardized metric for assessing the carbon efficiency of ships and identifying areas for improvement as well as the strategy that IMO will follow until to 2050 to reduce cardon emissions is shown to Figure 4.:

Figure 4: IMO 2050 Strategy



Source: IMO, 2011

1.3.2 The EEXI Regulation and the reduction of Vessel's speed

The EEXI (Energy Efficiency Existing Ship Index) regulation, implemented by the International Maritime Organisation (IMO), is designed to enhance the energy efficiency of ships that are already in operation. The EEXI formula is computed as an indicator that measures the energy efficiency of a ship relative to the predetermined maximum Energy Efficiency Design Index (EEDI) for newly constructed vessels (Bayraktar,2023).

The EEXI regulation is applicable to all vessels that fulfil the following conditions:

1. Ships with a Gross Tonnage (GT) equal to or greater than 400.
2. Ships not solely engaged in voyages within waters subject to the sovereignty or jurisdiction of the State whose flag they fly.
3. Ships propelled by mechanical means.
4. Ships not falling under category A of the International Code for Ships Operating In Polar Waters, 2016.

For this reason, the following solutions are proposed:

- Various solutions have been proposed and tested to reduce emissions in shipping.
- Older solutions have focused on mechanical interventions, such as the use of Energy Power Limitation (EPL) systems and Scrubbers.
- These efforts are insufficient to achieve the IMO's goals for 2030 and 2050.
- The use of alternative fuels is proposed, such as LNG, methanol, ammonia, and hydrogen.
- Alternative fuels are less harmful to the environment but face challenges that need to be considered. The equation 1 that is used to calculate the EEXI is:

$$EEXI\ \frac{Co_2\ emmissions\ (g\ Co_2)}{Benefit\ to\ society\ (tonnes\ x\ nm)} = \frac{Main\ engine\ emissions + auxilary\ emissions - aux.engine\ savings - main\ engine\ savings}{capacity\ of\ the\ ship\ x\ speed\ at\ loaded\ condition}$$

(Equation 1)

The ship's rate could be reduced through the implementation of mandatory regulations, namely by adopting the EEXI formula. However, this may give rise to another issue, namely the need to build a more efficient speed and direction for the ship. Furthermore, all regulations are founded upon the ship's fuel consumption. Therefore, the lower the ship's fuel consumption, the greater the potential for achieving higher environmental standards. Consequently, the ship would receive more favorable treatment from the International Maritime Organisation

1.4 Importance of weather routing system to avoid operational problems

Weather routing is a method that can be used to enhance vessel manoeuvres while still complying with all applicable environmental regulations. The process entails the utilisation of maps that display anticipated weather contours and ocean waves. Ships consume minimal amounts of fuel while they navigate within such protective enclosures, therefore avoiding the release of pollutants into the atmosphere. To minimise pollution levels and comply with the IMO regulations on shipping emissions, it is advisable to conduct the movement through safe corridors that are free from severe weather conditions. Weather routing systems assist ships in navigating efficiently and effectively, leading to improved energy efficiency and environmental impact (Kobayashi, 2014).

Minimising fuel usage and carbon emissions is of utmost importance within the International Maritime Organization's (IMO) jurisdiction due to various compelling factors (Garcia,2021):

1. Environmental sustainability involves reducing the fuel consumption of ships, resulting in a significant decrease in carbon emissions. This has a positive impact on addressing climate change and minimising the environmental impact of maritime industries. The IMO rules are established with the purpose of reducing emissions from the supply industry in order to mitigate global warming and ensure the stability of the maritime environment.
2. Complience to Regulations: In my view, ship owners and operators must prioritise fuel efficiency and carbon emissions to prevent negative outcomes, uphold the reputation of their businesses, and contribute to global sustainability initiatives as mandated by IMO regulations, utilising tools such as the Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII).

3. Cost Savings: Fuel is a significant factor in determining the operational value of transportation entities. Reducing petrol consumption leads to decreased expenses for fuel acquisition as well as ship management, enabling even tiny players to compete effectively in the market. By reducing the amount of petrol consumed, ships can travel longer distances without needing to stop and refill. This enhances their economic efficiency[9].

Weather routing plays a crucial role in decreasing fuel consumption and optimizing vessel operations by:

1. **Route Optimization**: Weather routing systems analyse meteorological data and oceanographic conditions to determine the most efficient routes for vessels. Ships can enhance their navigational efficiency and decrease resistance and fuel consumption by strategically avoiding adverse weather conditions, powerful ocean currents, and unfavorable sea conditions.
2. **Speed and Trim Optimization**: We route weather systems in order to provide recommendations for optimizing vessel speed and trim, therefore achieving optimal fuel efficiency. By modifying real-time weather forecasts, it is possible to alter these factors. This allows ships to adhere to their schedules while operating at their optimal fuel efficiency.
3. **Safety and Reliability**: Weather routing not only saves petrol, but also enhances protection by enabling ships to avoid severe weather conditions and dangerous areas. Vessels can enhance overall operating reliability by opting for more secure routes, hence reducing the risk of accidents, cargo damage, and crew injuries.

The incorporation of climate routing structures not only reduces fuel consumption and carbon emissions, but also improves vessel safety, performance, and compliance with IMO regulations. Aligned with worldwide efforts to combat climate change and encourage responsible maritime transport, it represents an accessible approach to environmental stewardship and sustainable transport methods.

CHAPTER 2: FUEL CONSUMPTION AND EFFICIENCY

2.1 Marine fuels

Maritime gas, often known as bunker fuel or ship gas, is a specific type of fuel used to power ships and other maritime vessels. Maritime fuel stands apart from fuels used in other transportation sectors, such as vehicle petrol or aviation fuel, due to its distinct requirements and characteristics specifically designed for maritime use. Marine petrol is typically denser and less processed than other fuels, and it comes in varied grades and specifications that rely on elements such as the kind of vessel, engine design, and regulatory requirements (Al-Enazi, 2021)

Key characteristics of marine fuel include:

1. **Density**: Marine fuels are regularly denser than different fuels to maximize power content in line with extent, as area is restricted on ships.
2. **Viscosity**: Marine fuels may additionally have higher viscosity to make certain right lubrication and green combustion in marine engines.
3. **Sulfur Content**: The sulfur content material of marine fuels varies relying on regulatory necessities and environmental issues. Low-sulfur fuels are more and more mandated to reduce air pollutants and follow emissions guidelines which includes IMO's sulfur guidelines (IMO 2020).
4. **Compatibility**: Marine fuels should be well suited with a wide variety of engine kinds and gas structures used in exclusive vessels.
5. **Storage and Handling**: Due to the big portions of fuel required for marine operations, garages and coping with centers must be designed to deal with the precise traits of marine fuels adequately (Kass,2022)

Marine petrol is essential for fueling the worldwide maritime sector, enabling the transfer of goods and people across oceans and rivers. In order to reduce emissions and increase environmental sustainability in the maritime sector, the composition and consumption of marine fuels are continuously changing in response to legislative changes and technological advancements. The selection of fuel types and the rate at which fuel is consumed are critical elements in marine operations, exerting significant influence on both the economic and environmental aspects of shipping. The main fuel types that vessels use are: a) Heavy Fuel Oil (HFO), b) Marine Gas Oil (MGO), c) Liquified Natural Gas (LNG) and d) Methanol, Ammonia and Hydrogen which are considered as the "Future Fuels"

HFO is the traditional gasoline utilized in maritime delivery, it has high viscosity and sulfur content, while contributing to air pollutants and it is the cheapest choice however subject to stricter environmental guidelines. MGO is a refined product with decrease sulfur content material as compared to HFO with higher fee but purifier burning, reducing emissions of sulfur oxides (SOx) and particulate depend. LNG is considered a purifier alternative to standard fuels. It produces decrease emissions of sulfur oxides (SOx), nitrogen oxides (NOx), and particulate count. On the other hand, in addition with the other types of fuels it requires specialized infrastructure for garage and dealing with. Lastly, the Future Fuels are emerging as ability alternatives to conventional fuels and each has unique characteristics and challenges regarding manufacturing, storage, and distribution (Brynolf, 2014).

2.2 Fuel Consumption

There are many factors that affect fuel consumption. To begin with, the Vessel Design and Efficiency is one of the most important factors because nowadays, modern vessel designs contain functions to enhance fuel efficiency, such as optimized hull shapes, bulbous bows, and advanced propulsion systems (Bertram,1998). The operational practices are also very important because, proper voyage making plans, pace optimization, and direction choice can appreciably impact fuel consumption. The efficient cargo handling, ballast management, and preservation practices also contribute to fuel savings. One of the most important and in many cases decisive factors is the Weather and Sea Conditions. Adverse weather situations, sturdy currents, and tough seas increase resistance and fuel consumption while, weather routing offerings help vessels navigate the most appropriate routes to reduce fuel consumption and voyage duration. Lastly, the regulatory compliance, includes the International Maritime Organization's (IMO) Emission Control Areas (ECAs) and the implementation of sulfur emission limits (e.g., IMO 2020), impact fuel selections and consumption styles.

The economic impact is that fuel fees constitute a big part of working fees for delivery agencies. At the same time, improving fuel efficiency reduces operational prices, enhances competitiveness, and improves profitability. We also need to refer to the environmental impact.

Reduced fuel consumption effects in lower greenhouse gas emissions, contributing to climate exchange mitigation while compliance with environmental rules promotes sustainable transport practices and decreases destructive environmental influences, together with air and water pollution. Lastly, regulatory compliance involves stricter environmental rules, such as emission gas fine requirements, which necessitate the adoption of cleaner fuels and improved gas efficiency measures.

2.3 Energy Efficiency Operational Index – EEOI

The International Maritime Organization (IMO) introduced the Energy Efficiency Operating Indicator (EEOI) to enable shipowners to assess a ship's fuel efficiency during its operation. The carbon intensity indicator, known as "CII" measures the level of demand for transport services (Tran, 2017)

The Energy Efficiency Operating Indicator (EEOI) is a measure of the carbon emissions produced during a planned voyage by a vessel. It is calculated by dividing the total carbon emissions for various conditions (such as ballast, cargo discharge, and full load departure) by the product of the amount of cargo transported and the overall distance travelled (Kristensen, 2023). The equation 2 presents the EEOI calculation formula of a vessel:

$$EEOI = \frac{Fuel\ consumed * Cf}{Cargo\ carried * Distance\ travelled} \quad \text{(Equation 2)}$$

, where Cf = fuel mass to CO_2 mass conversion factor.

With the increasing number of ships traversing the globe, the International Maritime Organization (IMO) has enhanced its environmental objectives and regulations. The International Maritime Organization (IMO) is actively working towards achieving its emission reduction targets for 2050 by employing the Energy Efficiency Operational Indicator (EEOI) as an effective assessment method for monitoring the energy efficiency of ships and their CO_2 emissions to the environment.

Connecting islands to the mainland has been a traditional practice in the maritime industry, as well as improving maritime connectivity by adopting new technologies and designing new vessels. Although the shipping industry plays a crucial role in sustaining the global economy, it is also a significant contributor to the emission of greenhouse gases and other forms of pollution. Greenhouse gas (GHG) emissions are the primary cause of global warming. Ships mostly emit carbon dioxide, which is the main greenhouse gas (GHG). During the MEPC 76 meeting, the IMO was unable to define a temporary goal, despite its previous objective of reducing shipping emissions by 50% by 2050, as compared to the levels recorded in 2008.

At MEPC 76, a specific timeframe was established for implementing long-term strategies to deal with the use of fossil fuels. However, the consensus is that the current short-term initiatives are not making substantial advancements in moving the industry closer to achieving net-zero emissions. Due to this perception, it is expected that governments, particularly the EU, would introduce laws requiring the shipping industry to reduce emissions, either through regulations or carbon fees.

The International Maritime Organization (IMO) has modified an international treaty known as MARPOL Annex VI to mandate more data reporting and slight reductions in emissions through the implementation of two separate procedures. These regulations are applicable to all cargo and cruise ships of a specific gross tonnage that are registered in a country that has signed the treaty and engages in global trade. The new regulations will go effective on November 1, 2022, and will undergo a review in 2026.

To begin using this strategy, the initial step is to decrease the carbon intensity indicator (CII). Consequently, shipowners are required to compute the carbon intensity indicator (CII) of each ship yearly and devise a strategy to reduce CII in order to meet the annual ship-specific benchmarks.

From 2019 to 2026, this CII strategy is expected to lead to a fleet decrease of about 11% in the compliance fleet. According to the International Maritime Organization (IMO), this aligns with their initial GHG policy for 2018, which seeks to decrease carbon emissions by 40% from 2008 to 2030. and achieve a 50%reduction in greenhouse gas (GHG) emissions by the year 2040. The Energy Efficiency Operating Indicator (EEOI) is a newly introduced metric that provides a framework for quantifying the energy efficiency of a vessel during its operational phase. The extent of the EEOI is wider than the present guidance on new ship energy efficiency, as it also emphasizes technical enhancements for ships that are already in operation (Yoshimura, 2015).

Marine pollutants encompass both water and air pollution. Although the latter sort of pollution had a negative reputation in the past, it quickly got assistance from a wide range of companies. The initial measure was integrating an assigned annex into the International Convention for the Prevention of Pollution from Ships, to reduce pollution caused by ships. The International Maritime Organization has persisted in its efforts and established several systems for monitoring emissions. An example of such a measure is the Energy Efficiency Operational Indicator, which was implemented to assist shipowners and operators in developing a framework to limit or reduce emissions from ships throughout their operation (Kristensen, 2013).

Implementing the Energy Efficiency Operational Indicator (EEOI) is an effective measure to mitigate global warming. The EEOI, or Energy Efficiency Operational Indicator, is a monitoring tool provided to shipping companies through the SEEMP, or Ship Energy Efficiency Management Plan, to supervise the performance of their ships and fleets over a specific time. The Energy Efficiency Operational Indicator (EEOI) can be understood as the amount of CO2 emitted per unit of work performed by a vehicle. Currently, numerous large vessels have become more energy-efficient about the amount of cargo they carry. To be accurate, 400,000 DWT bulk carriers are around 50% more efficient in terms of energy consumption per tone of cargo moved compared to 180,000 DWT Capesize vessels (Hansen 2020).

In order to gain a deeper comprehension of the functioning of EEOI, it is important to first grasp the concept of SEEMP. The implementation of a fleet energy performance approach is a business model that aims to build cost-effective strategies for improving fleet energy efficiency. The long-term SEEMP strategy utilizes the Energy Efficiency Operation Index (EEOI) to evaluate the effectiveness of ships and vessels. The EEOI, or Energy Efficiency Operational Indicator, is a tool that enables fleet managers to visually demonstrate the impact of operational modifications on their fleet's fuel use. The investigation focuses on two primary areas: the regular maintenance of propellers and the development of new propellers, as well as the invention of a waste heat restoration device. The ratio of CO2 emissions per unit of transportation artwork is utilized as a performance indicator for energy efficiency.

2.4 The Impact of Energy Efficiency Operational Index – EEOI in the Shipping Industry and Maritime Organizations

The EEOI guidelines have greatly benefited the transport industry. It enables fleet owners to assess the overall CO_2 emissions performance of their boats. The efficiency of greenhouse gas (GHG) emissions can be evaluated by using the Energy Efficiency Operational Indicator (EEOI), which is a widely accepted and standardized method for calculating a ship's carbon dioxide (CO_2) emissions. The issue of CO_2 emissions from ships was addressed by the International Maritime Organization (IMO) in 1997. The Marine Environment Protection Committee (MEPC) tasked the Committee with specifying, in accordance with Resolution A.963(23), measures to reduce greenhouse gas emissions from shipping. In order to limit and decrease greenhouse gas (GHG) emissions from worldwide shipping, the primary step is to implement a GHG assessment. This assessment will determine the GHG performance of a ship by analyzing its GHG emissions inventory. The Energy Efficiency Operational Indicator (EEOI) was developed as a method to measure a ship's GHG performance.

The EEOI utilizes CO_2 emissions as a metric to quantify the efficiency of power delivery in terms of performance. The document comprises metrics that exemplify a statistical methodology for assessing the efficacy of the service concerning its targeted strategy and overall performance. The prerequisites for establishing an EEOI are as follows:

- The Marine Environment Protection Committee determines when the EEOI must be launched.

- EEOI devises a plan to reduce the CO_2 emissions

- EEOI collects data to create a viable strategy

The final stage is to standardize the style. This streamlines the process of storing and analyzing information, allowing us to efficiently extract the precise data we require. The facts should encompass details regarding the specific fuel type utilized, the distance covered, and the quantity of carbon dioxide released. The precise distance travelled should be determined by utilizing the ship's logbook. To enable accurate analysis, it is necessary to record the specific type and quantity of fuel, the route covered, and the nature of the cargo on board. The impacts of climate change on the environment and human life are significant. These extensive recommendations intend to reduce greenhouse gas (GHG) emissions and enhance fleet efficiency.

While the EEOI is effective in addressing shipping emissions, it is equally important to support this statistical tool to improve the energy efficiency of ships. This is particularly important for the global shipping industry, which continues to expand during periods of economic growth, leading to concerns about energy consumption and greenhouse gas emissions (Marine Digital, 2013).

CHAPTER 3: FUEL CONSUMPTION PREDICTION AND ARTIFICIAL INTELLIGENCE TECHNIQUES

3.1 Fuel Consumption Prediction

The ship industry considers analyzing fuel use important due to reasons such as environmental conservation, energy efficiency, and long-term sustainability. There are multiple methods to accomplish this. The International Maritime Organization (IMO) has implemented various methods, such as the Ship Energy Efficiency Management Plan (SEEMP Part III), to forecast this product. This includes monitoring carbon intensity indicator (CII) targets for ships.

A highly successful approach to reduce fuel use is to implement weather routing, which entails selecting the most optimal route based on weather forecasts, delivery characteristics, and sea conditions. Weather routing can result in significant fuel efficiency gains, up to 3%, in addition to time savings (Taskar, 2020).

Ship velocity optimization is an alternative approach to reduce fuel usage. Research has indicated that the amount of fuel consumed is directly related to the cube of the cruising speed (Chaal,2018), however this relationship may vary under specific operational circumstances. Hence, it is important to enhance the velocity of ships while adhering to legal standards, such as the Energy Efficiency Existing Ship Index (EEXI) established by the International Maritime Organization (IMO), in order to maximize fuel efficiency.

The roughness of a ship's hull, caused by variables such as marine growth, increases the resistance and power needed to maintain speed, hence affecting the ship's fuel consumption. Regularly cleaning the hull and maintaining the propeller can significantly decrease fuel consumption by enhancing hydrodynamic efficiency. Additional methods to decrease fuel use in maritime operations include optimizing ballast and trim distribution, implementing power-saving devices such as the Mewis Duct, and utilizing machine learning approaches to forecast fuel consumption.

Various research has been conducted to assess and predict fuel consumption utilizing analytical models, regression analysis, and machine learning techniques. These techniques utilize operating information, environmental factors, and ship attributes to accurately estimate gas consumption.

Cepowski and Drozd in 2023 have conducted a study to discover the most effective method for estimating fuel consumption in different ship designs and operating conditions. This research compares physically-based models with information-driven models, including deep neural networks (DNN). The conclusion was that the use of Artificial Neural Network was more reliable than using Multiple Nonlinear Regression to estimate fuel consumption.

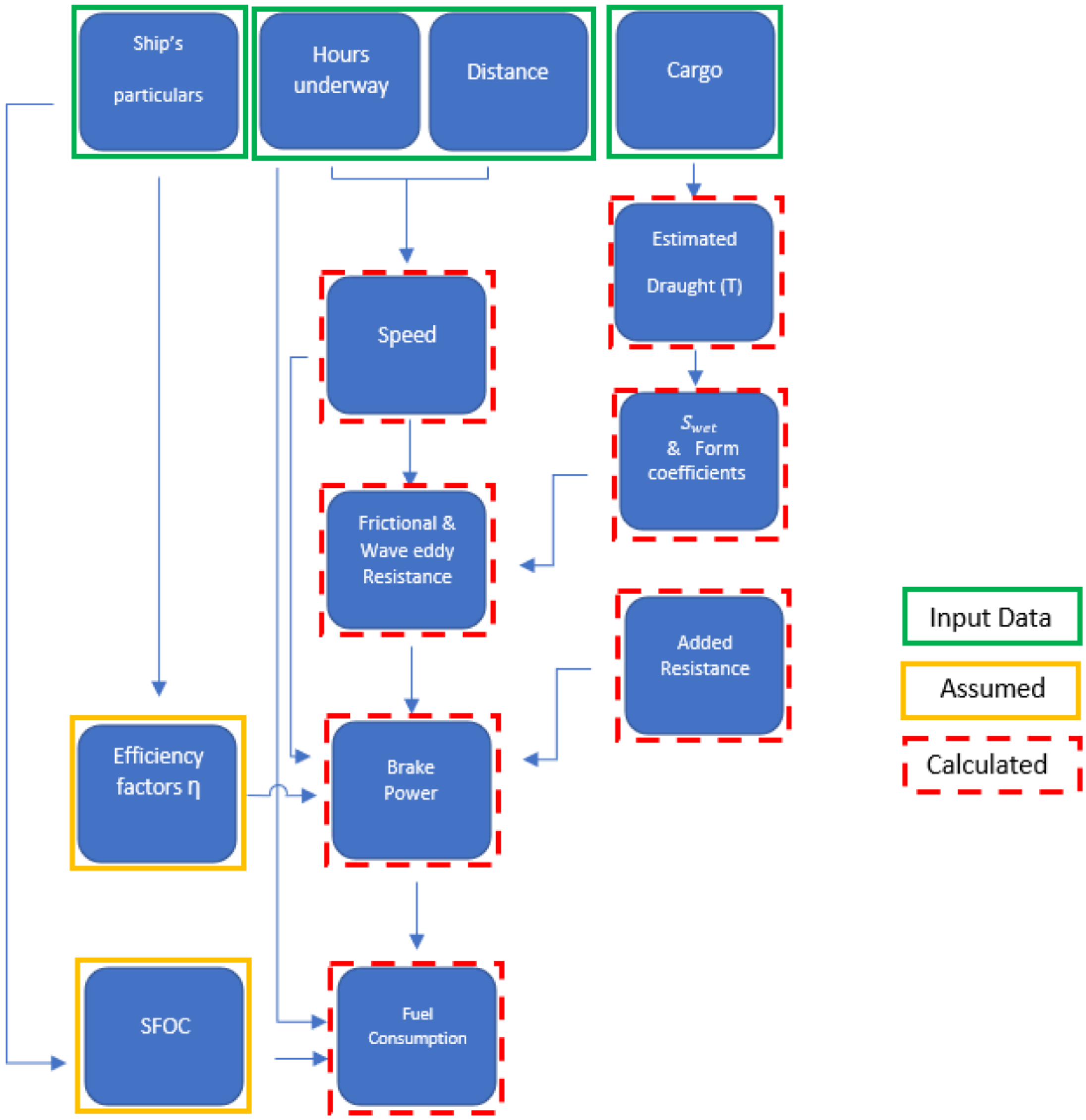
Overall, expertise and enhancing fuel efficiency in the shipping industry are crucial for increasing productivity, reducing environmental impact, and ensuring sustainable maritime operations (Cepowski,2023).

3.2.1 The Simplified Naval Architecture Method

Simplified Naval Architecture Method (SNAM) is a physical model that is used to predict fuel consumption in maritime activities. SNAM relies on a limited set of operational characteristics and assumptions to calculate gas consumption for different ship designs and operational situations. SNAM is specifically developed to be efficient and accurate, making it suitable for evaluating gas usage during voyage planning and optimisation. The estimation of petrol utilisation takes into account many factors such as ship features, ambient circumstances, and operating parameters (DTN, 2022). SNAM provides simplicity and clarity in its calculations, in contrast to more intricate statistics-driven models such as deep neural networks (DNN). Nevertheless, the accuracy of fuel intake estimations in certain scenarios may be influenced by simplifying assumptions and pre-installed settings (La Ferlita, 2023).

Figure 5 presents the main steps of SNAM. To begin with, it determines the resistance of the calm water via ship's approximate draft and the available information regarding the cargo being transported. Then, it determines the approximated added resistance caused by waves and wind. After that, the approximation of the efficiency factors representing the overall propulsion chain. Then, it determines the power of the brake via the total resistance obtained from step 1, the efficiency factor obtained from step 3, and the ship's voyage speed. Lastly, the estimation of fuel consumption is calculated via the product of the hours underway, the brake power obtained from step 4, and the approximated specific fuel oil consumption (SFOC) based on the ship's principal particulars. In maritime operations, the estimation of gas intake is accomplished using a modelling technique known as the Simplified Naval Architecture Method (SNAM).

Figure 5: Schematic representation of the SNAM



Source: Le Fertila, 2023

The calculation of a vessel's fashionable resistance and hydrostatic properties, which are two crucial factors impacting fuel consumption performance, relies on key principles derived from naval design. The operation of SNAM is divided into the Hydrostatic Characteristics Calculation, the Division of Total Resistance, the Calculation of Added resistance in waves, the Operational input elements, the Draft Determination and the Block Coefficient Calculation

- **Hydrostatic Characteristics Calculation (HCC)**: The HCC is a mathematical methos that is used to evaluate the stability and performance of floating or submerged structures. SNAM initiates the computation of a ship's hydrostatic properties in calm waters using proven methodologies such as the Holtrop and Mennen technique. This involves the identification of variables such as airflow and the area of the floor that is in contact with moisture.
- **Division of Total Resistance**: The division of total resistance refers to many components that contribute to the total resistance of a ship that moves throw water. The ship's total resistance (R_total) is separated into some of elements, inclusive of:
    - Frictional resistance (RF)
    - Form factor representing viscous resistance (k1)
    - Appendage resistance (RAPP)
    - Added resistance in waves (Rw)
    - Additional pressure resistance of a bulbous bow (RB)
    - Additional pressure resistance of an immersed transom (RTR)
    - Model ship correlation resistance (RA)
    - Wind resistance (Rwind)
- **Calculation of Added Resistance in Waves**: The calculation of added resistance in waves is an important factor in ship design. SNAM accounts for the additional resistance that a ship experiences when navigating through waves, which can significantly contribute to the overall resistance. The additional resistance is calculated using the STAWAVE-1 method, which considers the size of the vessel and the significant wave height.
- SNAM automatically accounts for wind effects by taking into account the ship's shape and wind velocity while estimating the usual resistance. Wind resistance may increase by 2% for bulk carriers, oil tankers, and specific types of vessels, but by 10% for containerships carrying stacked containers.
- **Operational input elements**: SNAM considers various operational aspects in every experience, including the duration of operation, the weight of the shipment, and the total distance travelled.

- **Draft Determination**: SNAM calculates the ship's draft during the journey by employing formulas that rely on characteristics such as propeller diameter and ship length. Utilizing draft calculations aids in the refinement of estimating hydrostatic characteristics and total resistance.
- **Block Coefficient Calculation:** The block coefficient is determined by considering the draft and other characteristics to measure the underwater volume of the deliver relative to its overall volume.

1. $R_{total} = R_P(1 + K_1) + R_{APP} + R_W + R_B + R_{TR} + R_A + R_{wind}$ (Equation 3)

- RF is the frictional resistance;
- $k1$ is the form factor describing the viscous resistance of the hull;
- $RAPP$ is the appendage resistance;
- Rw is the added resistance in waves;
- R_B is the additional pressure resistance of a bulbous bow;
- R_{TR} is the additional pressure resistance of an immersed transom;
- R_A is the model ship correlation resistance;
- R_{wind} is the wind resistance.

By calculating the added resistance in waves, the total resistance can increase in order to calm water resistance.

2. $R_{AWL} = \frac{P \cdot G \cdot H(\frac{w1^2}{3})}{16} B\sqrt{B/L_{BWL}}$ (Equation 4)

- B is the beam of the ship;
- ρ is the water density;
- $HW1/3$ is the significant wave height;
- $LBWL$ is the length of the bow on the waterline at 95% of B.

The increase of total resistance is increased to account the effect of of the wind.

3. $S_{WET} = L_{bp} \cdot (2T_{DD} + B) \cdot \sqrt{C_M} \cdot \left(0.453 + 0.4425C_B - 0.2862C_B - \frac{0.003467B}{T_{DD}} + 0.3696 \cdot C_{WP}\right) + 2.38\frac{A_{BT}}{C_B}$ (Equation 5)

- L_{bp} is the length between perpendiculars;
- C_M is the midship section coefficient for the sampled voyage;
- C_B is the block coefficient for the sampled voyage
- C_{WP} is the water plane area coefficient for the sampled voyage;
- T_{DD} is the draft for the sampled voyage;
- A_{BT} is the transverse sectional area of the bulb at the position where the calm water surface intersects the stem.

In order for Swet to be calculated, to maximum deadweight DWT and the corresponding Td is also taken into account.

4. $T_b = (D_p + e + 0.02L) \cdot 0.5$ (Equation 6)

- DP is the assumed propeller diameter, approximated as 0.65 of design draft;
- e is the distance of lower extremity of the propeller blades to the base;
- L is the ship's length.

5. $C_{Bd} = C_{BD} - C\frac{T_D - T_b}{T_D} \cdot (1 - C_{BD})$ (Equation 7)

- C=0.4;
- C_{BD} is the block coefficient at design draft;
- T_D is the design draft.

6. $T_L = T_D \cdot \left(\frac{\Delta}{\Delta_0}\right)^{(C_{BD}/C_{WD})}$ (Equation 8)

7. $C_{BL} = \frac{C_{Bb} - C_{BD}}{T_b - T_D} \cdot T_L + \frac{C_{BD} \cdot T_{BL} - C_{Bd} \cdot T_D}{T_b - T_D}$ (Equation 9)

- Δ is the approximated displacement during the voyage;
- CWD is the water plane area coefficient at design draft;
- ΔO is the approximated displacement of design draft.

The Specific Fuel Oil Consumption (SFOC) is a crucial factor that affects fuel usage in maritime operations. It quantifies the petrol consumption of the primary engine relative to the electricity generated, typically measured in terms of the engine's revolutions per minute (RPM). IMO has conducted a theoretical analysis that assumes a typical RPM is between 60 to 300. Based on the aforementioned method ,SNAM, IMO has obtained the following results as shown in Table 2.

Table 2: SFOC according to the IMO Greenhouse *Gas Study 2009*

Engine Age	**Power Output above 15,000kW**	**Power Output between 15,000 and 5000 kW**
Before 1983	205	215
1984-2000	185	195
2001-2007	175	185

Source: La Fertila, 2023

Table 2 shows that if the engine was built before 1983, only 205 had their output power above 15,000kQ and 215 between 15,000kW and 5000kW. In comparison with the engines that have been built between 1984-2000, 185 had power output above 15,000kW and 195 between 15,000kW and 5000kW. Lastly, the newest engines that have been built between 2001-2007 had 175 with power output above 15,000kW and 185 with power output between 15,000kW and 5000kW. In total, we can see a decrease in engines with power output above 15,000kW from 205 to 175 and with power between 15,000kW-5000kW from 215 to 185. The decrease happens with the same ratio in all the years that the study took place. The results are being showcased in the table below at table 3.

Table 3: The efficiency factors and their values

Efficiency Factor	Assumed Value
n_R(relative rotative)	(single scre)1.00-1.07 (twin screw) 0.98
n_H(hull) n_S(shaft) n_o(propeller-open water)	1.10-1.30 0.95-0.99 0.55-0.70

Source: La Fertila, 2023

3.2.2 The Deep Neural Network (DNN) Approach

The DNN (Deep Neural Network) technology is a machine learning method that has gained popularity in various disciplines, including maritime engineering, for accurately predicting fuel consumption and other performance metrics of ships. The DNN approach involves training a neural network model with multiple hidden layers using historical data. This allows for the analysis of complex patterns and correlations between input and output variables. Deep neural networks (DNNs) are a type of artificial neural network that consist of multiple hidden layers between the input and output layers.

This architecture enables them to analyze intricate patterns and relationships in data (La Ferlita,2022).In the area of estimating fuel consumption for ships, the DNN approach involves training a neural network model using historical data on ship operations, environmental conditions, and other relevant aspects. The model utilizes these data to generate forecasts for fuel use, relying on input factors such as vessel velocity, cargo weight, weather conditions, and route parameters. Here's a breakdown of ways the DNN approach works:

1. The model architecture of a deep neural network (DNN) has multiple layers of interconnected neurons, including input, hidden, and output layers. Every individual neuron in the hidden layers applies a nonlinear activation function to the weighted sum of its inputs, enabling the network to effectively capture intricate correlations within the statistics.
2. Training Process: The DNN model is trained using a technique called backpropagation, in which the model learns to minimize the discrepancy between its predicted gas intake values and the actual gas consumption seen in the training data. During the process of education, the model fine-tunes its internal parameters (weights and biases) in order to maximize its overall performance on a training dataset.
3. Activation Functions: Nonlinear activation functions can be included in the hidden and output layers to induce nonlinearity into the network. The typical activation functions are hyperbolic tangent, sigmoid, ReLU (Rectified Linear Unit), and its variations such as the smooth activation feature. These activation properties facilitate the community's understanding of intricate relationships between input and output factors.
4. Optimization Techniques: Typically, the DNN model is trained using optimization methods such as stochastic gradient descent (SGD) or its variants like ADAM. These algorithms update the parameters of the model largely by measuring the discrepancy between the predicted and actual values of petrol consumption. This process is repeated across several training rounds, known as epochs, resulting in an improved predictive accuracy of the model.
5. Data Preparation: Prior to training the DNN model, the input records need to undergo preprocessing and normalization to ensure that the model can effectively learn from the data. This involves dealing with missing values, adjusting input capacities, and encoding categorical variables.
6. Model Evaluation: After training the DNN version, it is assessed using a distinct validation dataset to measure its performance on new, unknown data. Metrics like as mean squared error (MSE) or coefficient of determination (R-squared) are commonly employed to evaluate the accuracy and generalization ability of a model.

An advantage of the DNN technique is its ability to capture nonlinear correlations and interactions between input variables, which may be difficult to characterize using traditional regression techniques. Deep neural networks (DNNs) have the ability to automatically extract functions from unprocessed data and adjust their internal representations to maximize forecast accuracy. To implement the DNN approach for predicting fuel consumption, the following steps are required :

- Data collection: Historical data on delivery operations, including fuel consumption, environmental factors, and operational variables, is gathered from several sources such as onboard sensors, logbooks, and operational records.
- Data preprocessing involves cleaning and computing the accumulated statistics to remove noise, handle missing values, and standardize the data for input into the neural network model.
- Model Training: The preprocessed data is utilized to train the Deep Neural Network (DNN) model, wherein the model's parameters are optimized to minimize the discrepancy between the predicted and actual values of petrol consumption. Typically, this task is accomplished by employing optimization methods in conjunction with stochastic gradient descent.
- Model evaluation: The Deep Neural Network (DNN) model is assessed utilizing validation data that was not utilized during training to measure its predictive capability. Metrics like MAE, RMSE, RSQUARED mean squared error or coefficient of determination are commonly employed to quantify the accuracy of a model.
- Deployment: After the DNN version has been trained and assessed, it can be implemented to generate real-time estimates of fuel consumption for new voyages using input data such as ship conditions, weather forecasts, and voyage information.

The DNN method offers a powerful and flexible framework for predicting gas intake in maritime operations, allowing ship operators to optimize their gas usage, reduce costs, and reduce environmental impact. However, powerful implementation requires careful information collection, preprocessing, and model tuning to make certain correct and reliable predictions. The input formulas for the machine learning approach are the following:

1. $y = xW^T + b$ (Equation 10)

- Y is the output vector
- B is the bias vector
- W is the weight

This is a function that allows all the layers to be counted.

2. $f(x) = x \cdot sigmoid(\beta\chi) = \frac{x}{1+e^{-\beta\chi}}$ (Equation 11)

This is a function that allows only few unimportant small weights to be added to the network

3. $W^*_n = w_n - a(\frac{\partial E}{\partial W_n})$ (Equation 12)

This is a function that allows the network to determine the updated weight, if that accurs

In study that has been posted by the Electronic Quality Shipping Information System, for a total number of 12.563 sample voyages, Table 3 lists the five ship topologies, a general cargo ship, an oil tanker, a containership, a RoRo ship and a Bulk carrier, chosen to generate the training data set. Table 4 also lists the associate number of ships as well as the number of voyages for each ship topology. The total amount of voyage samples in European waters was selected from the Electronic's Quality Shipping Information System database and from a publicly available emissions repost to ensure reaching a minimum threshold number of 10.000 samples needed for a consistent data set. The following results show us that the most common used ships for transportation are the RoRo ships where in our case, with only two available, 236 voyages have been made. The same happens with the containerships, where this only 300 available, more than 10.000 voyages have been made.

Table 4:Ship types considered to generate the training set and the associated number of ships and voyages

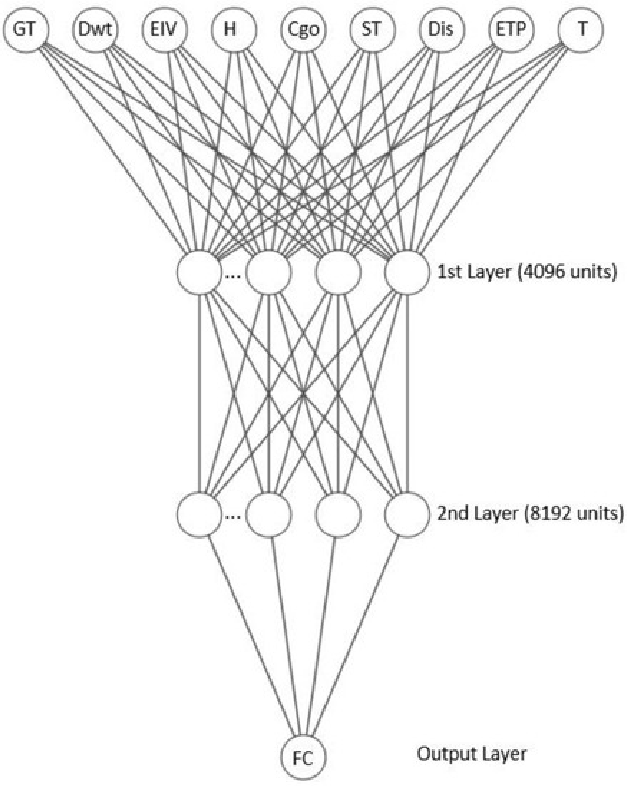
Ship Topology	Number of Ships	Number of Voyages
General Cargo ship	61	433
Oil Tanker	52	324
Containership	300	10.805
RoRo ship	2	236
Bulk carrier	147	765

Source: La Fertila, 2023

The neural network architecture of DNN approach, which is being displayed on Figure 4., is a network that is used for complex tasks. It has multiple input features, such as the GT, Dwt, EIV and more, which are processed to predict a targeted output. The first and second layer, allow the network to learn new patterns. The input variables to train the network architecture usually are:

- Gross tonnage (GT);
- Maximum deadweight (Dwt);
- Efficiency value (EIV);
- Hours underway (H);
- Cargo transported (Cgo);
- Ship type (ST);
- Distance (Dis);
- Engine total output power (ETP);
- Draft (T)

Figure 6: Representation of a DNN Network



Source: La Fertila, 2023

3.2.3 Comparative Analysis

The comparison between the SNAM (Simplified Naval Architecture Method) and the DNN (Deep Neural Network) technique for predicting ship fuel consumption intake yielded numerous insights and conclusions (Fujiwara, 2001):

1. Performance Across Ship Types: The DNN approach generally yielded predictions that were more accurate in estimating fuel consumption compared to the SNAM for various ship types, including bulk carriers, oil tankers, and Ro-Ro ships. The DNN approach demonstrated superior performance in terms of accuracy and reliability, particularly for bulk containers and oil tankers.
2. Challenges with Containerships: Containerships have challenges, yet the SNAM technique beat the DNN technique in estimating fuel consumption . The DNN technique encountered difficulties in accurately predicting the amount of fuel consumed by containerships, resulting in inflated or underestimated numbers relative to the specified values.
3. Loss Values and Training Process: The loss values obtained throughout the training process of the DNN model indicated that the learning process had reached convergence. The DNN model had to run many simulations in order to minimise the loss cost, demonstrating that the network learned to accurately estimate gasoline consumption.
4. Normalized RMSEs and Loss Values: Table 5 presents the results of the SNAM and DNN approaches in terms of normalized root mean squared errors (RMSEs) and loss values for different supply topologies. The SNAM validated much improved loss values for renowned cargo ships and containerships, indicating that the predictions were considerably less precise in comparison to other ship configurations.
5. Computational Efficiency: After training the DNN network the computational time needed to predict fuel usage for novel situations (unseen data) was extremely low, with predictions obtained within a few milliseconds. This emphasizes the efficacy of the DNN technique for real-time applications and decision-making in the maritime industry.

While both the SNAM and DNN approaches showed promise for predicting ship fuel consumption, the DNN approach demonstrated superior performance in many cases, particularly for bulk carriers, oil tankers, and Ro-Ro ships. However, challenges remain in accurately predicting fuel consumption for containerships using the DNN approach, suggesting the need for further refinement and optimization of the model for specific ship types.

3.3 Artificial Intelligence Techniques: Weather Routing

Historically, route optimization in logistics has relied on the manual and labor-intensive approach of utilizing the expertise of logistic operators to design and arrange transit routes. This technique involved analyzing maps, traffic patterns, and weather forecasts in order to determine the optimal routes. However, the chosen routes may frequently remain unaltered despite real-time modifications like as traffic or weather conditions, leading to inefficiencies and inaccuracies. During assessment, modern path optimization systems utilise advanced AI algorithms to analyze several factors and restrictions, providing optimized routes in a highly efficient manner. To begin with, the initial step is data gathering: Firstly, the programmers with the help of AI systems gather up-to-date information from several sources, including GPS, traffic updates, weather conditions, and historical route records, enabling a comprehensive understanding of the transportation environment.

Secondly, AI algorithms have the capability to process vast quantities of data and variables, much above the capabilities of previous methods, resulting in more precise and efficient direction optimization. Real-Time adjustments provide as a third alternative. AI-driven systems have the ability to change in real-time based on live traffic data, unlike static routes determined using traditional approaches. They adaptively modify routes to avoid congestion, accidents, or unexpected road closures, enhancing performance and dependability. Predictive analytics is utilized in the fourth model. AI utilizes historical data to evaluate the capacity of traffic patterns, weather conditions, and other variables that may impact transportation routes. This allows for proactive decision-making in selecting routes that are more efficient. Algorithms and forecasts are fine-tuned to maximize both accuracy and efficiency. Lastly, it is important to include hypothetical senario, since the most advanced systems incorporate this technology to offer real-time navigation and route details for various transportation methods. Additionally, augmented reality enhances situational awareness and provides more options for users.

In conclusion, it is evident that AI is transforming the course of logistics efficiency by offering convenient, scalable, and high-quality solutions for travel organizations to address dynamic challenges, enhance efficiency, enhance customer satisfaction, and promote the sustainability of their business (Marine Digital, 2024).

Route optimisation is essential for transportation firms since it directly impacts their performance, cost-effectiveness, and capacity to meet consumer expectations. Through the utilisation of artificial intelligence (AI) in optimising routes, organisations may effectively manage the intricacies of logistics networks and successfully navigate challenging circumstances such as unforeseen traffic conditions, road closures, weather disturbances, and transportation limitations. Some of the areas that AI assist in route optimisation are (NeuroSYS,2024):

- Advanced processing: AI algorithms have the capability to efficiently handle vast quantities of data and simultaneously analyse various factors, encompassing both static factors like distance and road conditions, and dynamic factors like traffic congestion, accidents, and weather conditions. These algorithms are designed to strike a balance between effectiveness and the limitations of implementation (Dikshit, 2023)
- Predictive Insights: AI can anticipate potential issues and disruptions in line with the intended course by analysing historical records and real-time data. For example, artificial intelligence algorithms have the ability to forecast tourist congestion by analysing past traffic patterns and current occurrences. This enables businesses to proactively adjust routes in order to prevent delays and optimise delivery timetables (How,2020)
- Integration of Multiple Modes: AI-driven route optimisation systems have the capability to combine many modes of transportation, including road, rail, and air, in order to determine the most efficient and cost-effective path for carrying goods. By evaluating the advantages and obstacles of each mode, artificial intelligence algorithms may enhance the entire delivery process and optimise performance to the fullest extent (Lipkova, 2022)
- Cost Reduction: By reducing the duration of the trip, fuel consumption, and all transportation expenses, the use of AI optimisation can result in significant financial savings for transportation companies. Improved and optimised routes can also decrease gasoline costs for all, streamline labour expenses, and generate additional profit and competitive advantage (Ridyadh,2024)
- Enhanced Customer Service: Expedited deliveries and dependable carrier services are crucial for maintaining customer satisfaction and loyalty. Route optimisation using artificial intelligence guarantees timely and efficient delivery, minimising the risk of delays and interruptions. Transportation companies can increase their reputation and

gain a competitive advantage in the market by efficiently assembling and delivering home windows while surpassing customer expectations. Artificial intelligence (AI) is crucial in optimising routes for freight transportation. It helps organisations negotiate intricate logistical networks, predict possible disruptions, and maximise efficiency, cost-effectiveness, and customer happiness. Incorporating state-of-the-art AI algorithms into route planning and execution processes is crucial for transport businesses aiming to remain competitive and prosper in the current dynamic business environment (Kumari, 2021)

AI is transforming weather routing optimisation by utilising sophisticated algorithms and machine learning approaches to analyse extensive data and provide precise forecasts about weather patterns and their influence on vessel performance. AI is being utilised to enhance weather routing and minimise fuel consumption.

1. **Data Analysis:** AI algorithms process historical and real-time data from many sources, such as weather forecasts, oceanographic data, and vessel telemetry. Through the analysis of this data, artificial intelligence (AI) can discern regularities and tendencies in meteorological phenomena, including wind velocity, wave amplitude, and oceanic streams, in order to enhance the precision of future weather forecasts.
2. **Route Optimization:** AI-driven weather routing systems utilise predictive algorithms to determine the optimal routes for ships, taking into account the present and predicted weather conditions in order to minimise fuel consumption. AI algorithms can determine the most efficient routes by taking into account variables such as wind direction, wave height, and current strength. These routes aim to reduce fuel usage while maintaining safety and punctuality.
3. **Real-Time Adjustments:** Artificial intelligence technologies constantly observe weather conditions and the performance of vessels in real-time. AI algorithms can adapt the intended course to save fuel usage and improve efficiency in response to unforeseen weather changes or unfavourable conditions encountered by the vessel.
4. **Learning and Adaptation:** Artificial intelligence systems have the ability to enhance future routing suggestions by analysing previous routing decisions and their results. Through the integration of feedback and the adaptation of their models using real performance data, AI algorithms can iteratively enhance their predictions and optimisation tactics, resulting in increasingly precise and efficient route planning.

5. **Integration with IoT Sensors:** AI-driven weather routing systems may seamlessly include data from onboard sensors and IoT devices to collect up-to-the-minute information on vessel performance, fuel usage, and environmental circumstances. By integrating this data with AI-powered analytics, shipping businesses may acquire more profound insights into their operations and make informed decisions based on data to enhance fuel economy and minimise emissions (Tien,2017)

CHAPTER 4: WEATHER ROUTING

4.1 Weather Routing Definition

In the ever-changing field of maritime transportation, the need to improve efficiency and minimize environmental harm has grown . Weather routing is an important concept that provides a methodical approach to minimize fuel usage and reduce operational expenses. This section explores the complex relationship between weather routing tactics and fuel consumption in the shipping sector.

Maritime operators incur substantial operational costs due to fuel consumption, which is further emphasized by its environmental impact in terms of emissions. To tackle this two-fold dilemma, it is essential to employ inventive approaches that leverage technological breakthroughs and predictive analytics. Weather routing is a complex system that uses meteorological data, vessel characteristics, and trip factors to determine the most efficient route while reducing fuel consumption. Maritime stakeholders can achieve significant improvements in fuel consumption and operational sustainability by effectively managing route planning, analyzing sea conditions, and understanding propulsion system dynamics.

The weather routing method commences by acquiring forecasts of weather conditions along the planned path. Subsequently, navigators evaluate the potential effects of these conditions on the vessel's performance, taking into account variables such as velocity, fuel usage, stability, and safety. In general, weather routing serves an important role in improving the efficiency, safety, and dependability of maritime transportation by assisting vessels in navigating challenging weather conditions while minimizing fuel consumption and environmental impact (DTN,2022).

The implementation of a contemporary weather routing technique is transforming maritime operations by providing enterprises with the chance to substantially decrease fuel consumption and the corresponding financial and environmental expenses. Historically, navigating the shortest distance between two ports was regarded as the most straightforward course. Nevertheless, progressive charterers, owners, and vessel managers now acknowledge that this strategy is not consistently the swiftest or most economical in terms of fuel use. Modern weather routing now utilizes precise and current meteorological data to optimize routes according to key performance indicators (KPIs), fuel economy goals, estimated time of arrival (ETAs), and other charter-party obligations.

Utilizing a data-driven approach not only reduces fuel consumption but also guarantees the safety of both the crew and cargo. Ships can optimize their trips and minimize their impact on the environment by avoiding unfavorable weather conditions and deliberately travelling through favorable winds and currents.

Weather routing now serves a dual purpose in marine operations. It not only helps vessels avoid unfavorable conditions, but also guarantees that each ship performs at its optimal performance. Weather routing is essential for sustainable and cost-effective shipping practices. It plays a crucial role in all stages of the journey, from pre-voyage planning to compliance, and can significantly reduce fuel use.

Charterers, shipowners, and cargo owners now have the choice to employ weather data both onboard and onshore to enhance their routes and improve operational efficiency. Accurate meteorological data is crucial, supported using maritime expertise. Forecasts are initiated using numerical weather forecasts data, which is subjected to a meticulous in-house post-processing approach. This technique integrates knowledge from marine meteorologists and former seafarers to consider intricacies such as currents, pirate-controlled straits, and other obstructions, ensuring a comprehensive route advice.

Contemporary weather routing technology enables captains to navigate more efficiently and with lower fuel consumption and emissions by continuously calculating the most environmentally friendly route throughout the journey. This equipment ensures that the planned direction remains optimal by incorporating up-to-date weather and sea conditions. It takes into account factors such as safety, performance, fuel consumption, estimated time of arrival (ETAs), speed and trim Designing routes is inherently complex, necessitating captains to balance multiple factors and limitations. The onboard weather routing equipment provides vital assistance to captains by helping them make informed decisions that match with their key performance indicators (KPIs) and operational goals. By utilizing these technologies, captains can navigate with a certain degree of chance while simultaneously optimizing performance and minimizing environmental impact (Yasakawa, 2015).

4.2 Maritime Technologies

Nowadays, there are many Maritime Technologies that most of the ships use. To begin with, the Artificial Intelligence System or AIS is a technology that simulates human intelligence such as learning and problem solving. It is initially a machine learning that utilizes algorithms to cognitive functions like language understanding (Harati-Mokhtari,2007). Another maritime technology is the Vessel Monitoring System or VMS which is a satellite system to track and monitor the location and movements of the vessels (Gibson, 2007). Lastly, the Long-Range Identification and Tracking system is similar to the VMS with the only difference being that the VMS is primarily is used to monitor fishing vessels in addition with the LRIT which is used to as an international tracking system (Verma,2009)

The procurement of maritime technologies has resulted in notable advancements focused on improving shipping safety, communications, and environmental conservation. An example of a recent advancement is the introduction of maritime informatics, which entails the integration, exchange, and analysis of ocean data using electronic instruments. The objective of maritime informatics is to streamline transportation operations, enhance maritime safety, and safeguard the marine environment by leveraging advanced technologies.

The main features of e-maritime informatics include enhanced bridge systems, standardized and automated reporting methods, improved reliability of navigation equipment, integration of accessible information through graphical displays, and connectivity to Vessel Traffic Advanced Services (VTS). The primary purpose of the reduced-size e-navigation device is to utilize the Electronic Chart Display Information System (ECDIS), which serves as the foundation of the navigation system. ECDIS provides comprehensive navigation guidance for maritime workers by integrating onboard sensors with additional data. Furthermore, e-navigation encompasses real-time analytics, route planning, and decision support systems to ensure optimal transportation practices and environmental management. Desired objectives for electronic transportation One crucial objective is to mitigate collisions, land and marine issues, hence decreasing the pollution which is cause by the ships transfers. The shipowners have the ability to discover techniques to reduce petrol use and emissions, so advancing environmental sustainability objectives.

Although e-navigation shows great potential for improving safety and environmental protection, there are still significant challenges in terms of operational issues. Ongoing research and development are focused on resolving the responsibility for navigation decisions and incorporating shore-based traffic control systems. Although faced with challenging circumstances, the significant benefits of e-navigation in optimising navigation and reducing greenhouse gas emissions highlight its crucial role in determining the future of marine navigation (ECDIS Benefits, 2024)

The Convention for Safety of Life At Sea (SOLAS) introduced the substitution of paper charts with authorized electronic charts. Electronic Chart Display and Information Systems (ECDIS) signifies a noteworthy transformation in marine navigation methodologies. According to this requirement, paper charts will only be used as backups or on smaller vessels, while ECDIS will be the main navigation instrument for larger ships.

ECDIS serves the purpose of not only presenting electronic charts, but also incorporating crucial ship data from sensors, including speed, water depth, and position. This integration allows sailors to have a thorough understanding of their surroundings. In addition, ECDIS has the capability to integrate radar, Automatic Radar Plotting Aids (ARPA), and Automatic Identification System (AIS) data, thereby improving navigational safety and efficiency.

From a perspective of energy efficiency, ECDIS has numerous benefits. It allows for accurate mapping and tracking of the ship's location in real-time, making it easier to plan the best path and stay within predetermined safety areas. By establishing a connection with track pilots, Electronic Chart Display and Information System (ECDIS) improves the vessel's capacity to maintain precise course accuracy, hence minimizing the distance covered and diminishing the release of greenhouse gas (GHG) emissions.

The passage plan is an essential component of voyage planning, necessary for determining the most efficient route and improving overall efficiency. ECDIS plays a crucial role in the planning and execution of a voyage, contributing to every step of the process:

- **Appraisal**: The master, in consultation with navigating officers, assesses the intended voyage comprehensively.
- **Planning**: Navigating officers develop a detailed plan covering the entire voyage, including areas where pilots will be on board.
- **Execution**: The finalized voyage plan is executed.
- **Monitoring**: Continuous monitoring of the vessel's progress along the pre-planned route.

In order to conserve energy, route planning should take into account other elements such as avoiding shallow areas and unfavorable sea currents. Hence, it is imperative to incorporate fuel-efficient practices into passage planning, commencing from the evaluation phase.

Weather guidance, initially created by naval ships during the naval age, has significantly enhanced due to advancements in weather forecasting technology. Real-time satellite data has revolutionized the weather pattern, resulting in better accuracy and efficacy in optimizing shipping channels. In summary, incorporating energy-efficient practices into road design through the utilization of technologies like ECDIS and climate strategies is crucial for decreasing fuel usage, improving safety, and promoting environmental sustainability within the maritime sector.

Weather tactical services offer fleet owners and charterers a range of strategic alternatives tailored to their specific needs, taking into account elements such as cargo type, vessel type, operating location, and charter party status. Nevertheless, it is important for the shipowner to maintain ultimate control over sailing decisions and have the ability to ignore the recommendations of weather forecasting agencies if they perceive it as a threat to the safety of the ship, cargo, or workers on board.

Weather forecasting service providers frequently utilize computerized vessel modelling and get vessel-specific data from owners in order to align with the route plan. This encompasses ship attributes and historical information on meteorological circumstances such as present conditions, wind speed, atmospheric pressure, temperature, and wave amplitude. Furthermore, the dataset incorporates climatic data obtained from both state and commercial sources.

4.3 Route Optimization Strategies

The indicated technological solutions for optimizing vessel routes provide a comprehensive approach to maximizing efficiency and minimizing costs in marine operations. Each strategy has a role in optimizing the route (NeuroSYS, 2024).

1. **Utilisation of contemporary route planners**: Advanced course planning tools such as Tranzas' Navi-Planner, StormGeo's Bon Voyage System, and OneOcean's PassageManager offer transportation businesses with up-to-date maps, weather predictions, and estimated time of arrival (ETA) estimates. By utilizing these gears, organizations can gain knowledge on the most fuel-efficient and time-saving routes, resulting in cost savings and improved operational performance.
2. **The utilization of weather routing**: Those services are crucial in minimizing the impact of adverse weather conditions on the performance of vessels. Wayfinder and SofarOcean utilize data from an extensive network of weather sensors to enhance routes based on real-time weather predictions. Ships can decrease their fuel consumption and minimize delays by successfully dealing with adverse climate conditions, ultimately resulting in reduced operating costs.
3. **Big Data analysis**: The study of large datasets provides valuable insights into optimising routes by providing up-to-date information on weather conditions, navigation suggestions, and actual travel data. Through the analysis of vast datasets, ship operators may make informed decisions to optimize routes, improve fuel efficiency, and better overall voyage management.

By incorporating these technological solutions into their operations, shipping businesses can attain substantial enhancements in fuel efficiency, cost reduction, and productivity. In order to remain competitive in the maritime business and effectively address strategic challenges, it is crucial to embrace technology-driven solutions.

4.3.1 Weather Routing onboard

Weather routing on board is accomplished by utilizing cutting-edge navigational equipment and dedicated software tools specifically intended to optimize routes based on real-time weather and sea condition data (Kobayashi, 2014). The operational process is based on the following steps:

1. **Data collection**: The process begins by collecting relevant data, such as weather forecasts, oceanographic data, ocean currents, wind patterns, and other environmental parameters. This information is obtained from multiple sources, including the weather provider, satellite observations, and shipboard sensing instruments.
2. **Data Processing**: After being accumulated, the records are processed and analyzed to obtain precise updates of the current meteorological conditions along the route of the delivery. Weather forecasting utilizes numerical models and sophisticated algorithms to anticipate the development of weather patterns during a specific period.
3. **Route optimization**: The on-board weather forecasting software programme utilizes the processed information to continuously compute and optimize the most effective direction for the delivery of goods. This takes into account factors such as fuel consumption, duration of the trip, safety measures, and adherence to charter party terms. The software programme evaluates the vessel's performance, taking into account factors such as velocity, fuel efficiency, and seaworthiness.
4. **Decision Support**: Weather forecasting software provides valuable decision support capabilities for captains and teams. Displays graphics illustrating the recommended path, as well as alternative routes and probable hazards or problematic locations. Captains have the ability to engage with the software programme in order to adjust parameters and enhance the direction according to their preferences and operational objectives.
5. **Execution**: After choosing a route, the navigational system on the ship guides the vessel along the predetermined path, continuously monitoring weather conditions and making real-time adjustments as necessary. This may also involve changing course to avoid inclement weather or taking advantage of favorable conditions to optimize velocity and fuel efficiency.

Onboard weather routing enables captains to make informed decisions that optimise the vessel's typical performance, save fuel consumption, enhance safety, and ensure timely arrivals at their destination. By utilising advanced technology and precise weather data, ships can navigate more efficiently and effectively, resulting in cost savings and promoting environmental sustainability in marine operations.

Onboard routing structures enable captains to calculate the optimal route with the least amount of experience, while giving priority to safety. These systems utilise real-time meteorological data and vessel performance indicators to compute optimal routes, taking into account aspects such as fuel consumption, journey duration, and potential hazards. Through the utilisation of advanced algorithms and predictive modelling, captains can confidently navigate, ensuring minimal fuel consumption and maximum economy without compromising safety.

4.3.2 Weather Routing onshore

Onshore monitoring systems use combined vessel data to provide comprehensive performance evaluation to fleet operators, operations managers, and performance managers. These structures provide valuable insights into the overall performance characteristics of the entire fleet, identifying areas for improvement and optimising operating efficiency. Shore-based personnel can enhance overall fleet performance by studying data from multiple vessels to identify superior practices and strategies for improvement.

In addition, onshore dedicated routing companies play a crucial role in providing the most suitable route guidance to ships. By utilising the knowledge of seasoned master mariners and nautical meteorologists, these teams provide personalised course recommendations specifically tailored to the specific voyage requirements. Onshore routing groups ensure that vessels can navigate precisely and efficiently by considering factors such as weather patterns, sea conditions, and navigational hazards. Their goal is to maximise operational success while minimising risks.

In addition, onshore dedicated routing personnel play a vital role in providing optimal navigation guidance to vessels. By utilising the expertise of seasoned master mariners and nautical meteorologists, these teams provide customised course suggestions that are specifically designed to meet the unique requirements of each voyage. Onshore routing groups consider elements such as weather patterns, sea conditions, and navigational hazards to ensure that vessels can navigate with precision and efficiency, hence maximising operational success and minimising risks.

4.4 Path-finding algorithms

The Pathfinder algorithm is a graph searching algorithm and its main use is to find the shortest path between two points A and B. It explores possible routes by evaluating many parameters, prioritizing those with the lowest cumulative cost. The main characteristics are the graphs as the algorithm operate on graphs by representing locations and the connection of paths between them. Many different versions of the Pathfinder algorithm use different search strategies, with the most common one being the A-star algorithm. Lastly, the heuristic function helps to estimate the cost of the transfer (Foead,2021)

Another important algorithm that many ship companies use nowadays is SIMROUTE. SIMROUTE is an open-source software that uses A* pathfinding and the Copernicus Marine Environment Monitoring service in order to optimize shipping routes. By doing that, it minimizes navigation time, fuel consumption and gas emissions. The Data Integration and Route Optimization system that SIMROUTE uses is very efficient. Firstly, it downloads all the required sea state data from CMES which then, with the use of A* algorithm optimizes the best route for a voyage based on water resistance in order to minimize the travel time and of course fuel consumption and gas emissions. On the other hand, it uses a STEAM2 tool, which is an emissions model to estimate pollutants like CO_2. This tool also provides safety modules to minimize risks related to waves (Grifoll, 2022).

Path-finding algorithms can be broadly categorizes into informed and uninformed search strategies, with each category having each strengths depending on its application. To begin with, uninformed algorithms such as Breadth-First Search and Depth-First Search, don't usually require any more information for exploring new paths. This makes them more suitable for less complex searches. By using this method, the efficiency is optimized by prioritizing paths that most of the times appear to be mor promising. Additionally, the heuristic function in algorithms such as A*, plays a crucial role as it calculates the remaining distance and of course the voyage time (Sidhu, 2020)

Lastly, another crucial part of path-finding algorithms is the real time dynamic routing, particularly for maritime and logistics industries. Nowadays, many new algorithms, such as SIMROUTE, integrate real time environmental such as wind speed and wave height in order to adapt into the various weather conditions. This allows them to ensure a safe voyage with the lowest of course fuel consumption (Hashali, 2024).

4.5 Weather Routing: Fuel Consumption Savings

Saving fuel through weather routing offers a range of benefits for charterers, shipowners, operators, and the environment (Kobayashi,2023):

- **Cost Reduction**: One advantage of using weather solutions to decrease fuel consumption is cost savings. Fuel is a significant component of a ship's operational expenses, hence any decrease in fuel usage directly results in a decrease in operating costs.
- **Environmental**: Minimizing fuel use leads to a decrease in the release of greenhouse gases and other harmful substances from ships. This contributes to the preservation of the environment and mitigates the shipping industry's influence on climate change and air pollution.
- **Compliance**: The International Maritime Organization (IMO) has implemented stringent environmental standards that mandate ships to decrease carbon emissions and enhance fuel economy, resulting in a beneficial outcome. Implementing a climate approach can assist fleets in meeting regulatory requirements through the enhancement of fuel economy and reduction of emissions.
- **Improved logistics efficiency**: By optimizing the navigation of ships in favorable weather conditions, it is possible to decrease travel time and reach the target more quickly. This does not inevitably result in cost reductions, not just in terms of fuel expenses, but also in terms of operational effectiveness and fleet productivity.
- **Improved Safety**: Climate solutions take into account both fuel efficiency and safety factors. The adoption of safer routes and the avoidance of bad weather conditions effectively reduces accidents, vessel damage, and personnel injuries.
- **Better itineraries**: Weather predictions offer essential information about the upcoming weather and sea conditions along the planned route. This enables charter operators to enhance trip planning efficiency, minimizing disruptions and optimizing the planning process.
- **Competitive Advantage**: Companies that use climate solutions to reduce fuel consumption get a distinct competitive edge in the marketplace. By enhancing environmental efficiency and lowering operational expenses, we can offer consumers economical and environmentally-friendly shipping options.

All the above can be highlighted through three basic benefits of saving fuel through weather routing, based on the economic, environmental and operational advantages.

1. **Reduced costs**: Efficient weather routing can result in substantial fuel conservation, with potential savings of 2-5%, contingent upon multiple factors. If a vessel consumes 50 tonnes of fuel daily, a 5% reduction in fuel consumption might lead to significant cost savings of more than $8,500 on fuel expenses for a seven-day journey, assuming a bunker price of $5,000 per tonne.
2. **Reduced Emissions**: Reducing fuel usage leads directly to a decrease in emissions, which in turn contributes to the promotion of environmental sustainability. Research indicates that the shipping industry has the potential to decrease emissions by as much as 55% by implementing strategies that focus on reducing fuel consumption. Utilizing measures like as speed reduction and weather routing can result in emission reductions of approximately 1-4% and 17-34%, respectively. These reductions in emissions can lead to substantial cost savings of up to €280 per metric tonne.
3. **Efficiency Optimization**: Weather routing guarantees that strategies to save fuel do not affect the effectiveness of operations. By taking into account the key performance indicators (KPIs) of a voyage, such as fuel consumption, estimated time of arrival (ETAs), and charter party agreements, it is possible to choose the most efficient routes that minimize fuel usage without compromising safety or adhering to the schedule. This strategy enables ships to cruise with optimal efficiency, resulting in fuel conservation and cost reduction.

All of the above benefits underscore the importance of integrating weather routing strategies into operations achieve economic, environmental and operational objectives simultaneously.

4.6 Weather Routing: Energy Efficiency Operational Index – EEOI

The maritime sector, has always faces challenges in complying with the environmental regulations. The IMO established in 2009 the Energy Efficiency Operations Index (EEOI) to measure the energy efficiency of the global fleet. EEOI measures carbon dioxide emissions produced by a ship and it is usually expressed in ton-miles. Many strategies have been initiated to reduce carbon dioxide emissions as many studies have shown that by reducing speed by 10% can lead up to 20% decrease in fuel consumption. Efforts to build and showcase environmentally friendly vessels for international shipping will persist as new challenges emerge due to the rapid growth of world trade and the increasing need for maritime transportation. Designers have a vast field to explore through ongoing study and development. Emerging technologies such as artificial intelligence, Internet of Things (IoT), data analytics, machine recognition, and location services are crucial in realising the desired goals, as they possess significant potential. Furthermore, commercial software tools can help by calculating and comparing EEOI costs before and during voyages, while at the same time providing insights into operational efficiencies.Lastly, an important aspect of IMO reform should be on implementing a diverse range of laws and assessing their impact on individuals, the environment, and stakeholders in global marine ecosystems.

4.7 Weather Routing: Challenges and Risks

Accurate weather routing records are paramount for optimizing fuel consumption and ensuring green voyage planning. When routes aren't optimized based on dependable weather records, vessels might also emerge as taking longer paths or navigating through unfavorable weather situations unnecessarily. This can significantly impact fuel consumption, as ships may consume greater fuel to navigate around storms or detrimental situations, leading to elevated operational prices and emissions. Furthermore, the selection of route could have a great effect on a voyage's profitability. For example, different routes may also provide various time financial savings, but detrimental weather conditions along those routes can negate any potential benefits. Therefore, it's important to strike the right balance between minimizing transit instances and fuel intake while prioritizing group and vessel protection. Dynamic velocity routing provides a possibility to enhance efficiency via adjusting vessel speeds based totally on facing weather situations. However, without accurate weather records, vessels may also be insufficient to navigate round severe weather as opposed to optimizing pace, ensuing in expanded fuel utilization, emissions, and usual operational charges. In essence, correct weather routing information enables vessels to make knowledgeable selections that optimize fuel consumption, limit transit times, and make sure price-effective and environmentally sustainable voyages (Sofar Ocea, 2022).

Inaccurate weather routing statistics can indeed cause unoptimized routes and useless gas consumption, as vessels may end up taking longer or much less efficient paths because of unreliable forecasts. This no longer only will increase operational charges, however, also contributes to better emissions. Moreover, deviations from planned routes can pose challenges in meeting key performance signs (KPIs) which include fee targets and estimated time of arrival (ETAs), particularly if damaging climate situations disrupt the voyage agenda. It's critical for maritime operators to have get admission to correct and timely climate statistics to reduce these dangers and make certain efficient and safe navigation.

Inacurate weather routing information can ose several risks to maritime operations, such as:

1. **Safety Concerns**: Inaccurate weather predictions or navigation suggestions can expose vessels to hazardous situations, such as storms, strong winds, or rough waves, thereby endangering the safety of the crew, passengers, and cargo. Operating in adverse weather conditions heightens the risk of injuries, collisions, and damage to vessels.
2. **Increased Fuel Consumption:** Deviation from accurate routing information may expose vessels to unexpected weather patterns or hazardous currents, resulting in suboptimal courses. This inefficiency can result in more fuel consumption, since ships may need to change their course or manoeuvre through stormy seas. This eventually leads to higher operational costs and a greater environmental effect.
3. **Delays and Schedule Disruptions**: Erroneous weather routing data can lead to delays and interruptions in cruise itineraries. Adverse weather conditions may necessitate vessels to alter their intended courses or reduce their speed, resulting in missed port visits, longer travel durations, and possible contractual fines for delayed deliveries.
4. **Environmental Impact**: Incorrect meteorological data can lead to inefficient routing, causing excessive fuel usage and higher emissions, which contribute to environmental pollution and climate change. Increased fuel consumption results in the emission of a greater amount of greenhouse gases into the atmosphere, hence worsening the carbon footprint and environmental impact of the industry.

5. **Financial Losses**: Inadequate weather routing decisions can result in monetary losses for shipping businesses as a consequence of escalated fuel expenses, delays in schedules, and the possibility of harm to boats or cargo. Furthermore, there is a possibility of legal obligations if the provision of incorrect routing information leads to accidents, environmental contamination, or failure to comply with legislation.
6. **Reputation Damage**: Shipping businesses who regularly have issues as a result of incorrect weather routing may face harm to their reputation and trustworthiness.

In order to reduce those risks, transportation authorities should allocate resources to reliable climate forecasting systems, hire experienced meteorologists and navigators, and implement strong threat management policies to guarantee precise and timely weather routing data. Furthermore, continuous education and training for crew members on climate analysis and emergency response tactics are crucial for improving safety and operational adaptability at sea.

CHAPTER 5: WEATHER ROUTING CASE STUDIES

5.1 AI driven route optimization tool: OptiNav by True North Marine and IVADO

OptiNav is an advanced software system for navigation optimisation. It was developed by True North Marine (TNM) in partnership with IVADO and esteemed professors from top Canadian universities. The purpose of OptiNav is to enhance climate strategies and reduce carbon emissions in the marine industry. It addresses environmental challenges while simultaneously improving operational efficiency and profitability.

Optinav undertook rigorous testing with 15-20 offshore organisations throughout the beta phase, resulting in remarkable outcomes. The software solution routinely achieves fuel savings within the range of 5-10%. This leads to lower daily petrol consumption throughout the year for various fleet types, as indicated by the distribution. Therefore, these cost reductions have substantial consequences for the preservation of the environment and any advantages in terms of operations.

OptiNav utilises sophisticated artificial intelligence algorithms, which have been collaboratively created with TNM and IVADO, to achieve a variety of distinct goals that effectively manage cost considerations, conservation efforts, and the reduction of greenhouse gas emissions. Revamp Optinav's Ivado AI projects competence. Assists in the creation of advanced digital solutions that can optimise methods while also minimising environmental impact.

EVADO is a team managed by the Université de Montréal that focuses on multidisciplinary training and information management. The team includes four college colleagues and their main goal is to collaboratively build and promote AI solutions that are strong, logical, and ethical. Evado fosters collaboration between research centres, regulatory organisations, and corporate sponsors to promote innovation and the implementation of AI technology in regional and international contexts.OptiNav is a notable breakthrough in marine optimisation, providing advanced AI-driven route optimisation capabilities combined with human knowledge. The capacity to effectively manage financial concerns, safety considerations, and environmental impact renders it an invaluable instrument for addressing the intricate issues of contemporary maritime operations.

OptiNav features

OptiNav boasts several extraordinary skills that contribute to maritime excellence:

1. Customizable Goals: Users can specify their optimisation objectives, such as minimising travel cost, reducing travel time, lowering emissions, or a customised combination of these aspects.
2. Commercial Objectives: OptiNav has developed a cutting-edge module that adheres to constitutional birthday party warranties. It takes into account the most efficient vessel route without any contractual limitations, therefore optimising business objectives.
3. Holistic Approach: OptiNav encompasses all stages of the journey, starting from pre-voyage planning to real-time actionable guidance throughout the trip, ensuring a comprehensive and smooth optimisation process.
4. Human-in-the-Loop: TNM Analysts, many of whom possess expertise in maritime navigation, serve as crucial middlemen between customers and OptiNav. Their data guarantees top-notch solutions and real-time anomaly identification throughout the optimisation process.

Furthermore, Optinav harnesses cutting-edge technologies to enhance its capabilities:

Integrated Weather Forecasting integrates meteorological and oceanic studies to facilitate dynamic navigation, enabling ships to adjust their courses based on changing weather conditions for optimal performance.

Database for Monitoring Vessel Performance: OptiNav utilises a sophisticated database to chart the performance of vessels in various weather conditions, enabling real-time optimisation to identify the most effective solutions.

Risk assessment: Advanced route-locating methods utilise a wide range of environmental factors, such as the International Maritime Organization's emission control zones, to assess risks associated with selected routes and their degradation. Optinav revolutionises maritime transport by integrating customisable value chains, operational flexibility, a holistic approach, and modern technology. This new framework ensures optimal performance, cost effectiveness, and environmental sustainability in the transportation sector.

True North Sea is committed to promoting a sustainable future and actively participates in collaborative initiatives with Green Marine and the United Nations Global Compact. They actively engage in global initiatives to promote environmental responsibility and sustainability within the maritime sector, demonstrating their commitment and collaborative approach.

By integrating its substantial knowledge in marine affairs with state-of-the-art technology True North Marine aims to tackle the decarbonisation challenge in the industry by offering cutting-edge services and products that not only contribute to reducing carbon emissions but also create added value to its customers.

In the future, True North Marine will continue to be at the forefront of efforts aimed at reducing the environmental impact of marine activities. The company will make a concerted effort to lead by example and work together with industry partners to promote positive change and contribute to a more environmentally friendly and sustainable marine industry and planet. According to the analysis conducted in this paper, Optinav appears to be the most advanced and innovative method for optimising maritime transportation. This partnership between True North Marine and Evado, with input from esteemed academic experts, showcases a strong commitment to utilising contemporary technology and expertise to address crucial maritime concerns and ensure the effective implementation of the solution. Transforming the product into a fixed gas investment that yields savings ranging from five to ten percent. Optina utilises advanced AI algorithms to emphasise its efficacy and potential influence on environmental sustainability, productivity, and performance. It practically implements a multi-objective model that provides value, safety, and balances diversity and greenhouse gas emissions. Optina showcases a comprehensive approach to optimising mobility.

OptiNav's versatility and flexibility are showcased by its key features, which include customisable goals, an emphasis on performance goals, and real-time recommendations. These elements allow OptiNav to effectively cater to a wide range of consumer preferences. Furthermore, the integration of meteorological data, analysis of fleet performance, and evaluation of potential risks demonstrates a complete strategy for enhancing operational efficiency and managing risks.

In conclusion, OptiNav is a significant breakthrough in the field of marine optimisation. It offers a comprehensive solution that combines AI-driven algorithms, real-time data, and expert human input. The maritime industry greatly benefits from its ability to generate cost savings in electricity, enhance performance, and contribute to environmental sustainability, making it an invaluable asset.

5.2 Optimizing global shipping with the SOFAR Ocean Marine Weather Forecast and Pathfinder tool

Shipping businesses worldwide are continuously striving to enhance performance. Practically, this entails minimising expenses, preventing delays, and complying with legal requirements like the IMO GHG Strategy, all while ensuring safe operations. The presence of unpredictable marine weather exacerbates the challenges posed by these intricate and occasionally contradictory agendas.

Severe weather phenomena, like Hurricanes Harvey, Irma, and Maria, pose substantial and inevitable difficulties for logistics companies. For example, Hurricane Harvey resulted in the closure of Port Houston, Texas for a duration of six days, while ports in Georgia and Florida were closed for three days due to the impact of Hurricane Irma. The process of global shipping is meticulously coordinated; the closure of a significant port can have far-reaching effects on shipping routes worldwide.

Not just significant weather occurrences, but also other factors might cause problems for shipping firms. Global shipping routes can be negatively impacted by fog, wind, and ice. Despite the use of contemporary technological navigation aids, ships at sea typically decrease their speed when encountering foggy conditions. This will result in a delay in the ship's arrival at the port or necessitate the ship to accelerate under favourable weather conditions in order to make up for lost time. "This leads to increased fuel consumption and higher fuel expenses," clarified Maritime Studies South Africa.

The benefits, as outlined by the SOFAR specialists, are as follows:

1. Minimise petrol use through an optimised route: Weather forecast agencies analyse current and predicted weather conditions along transportation routes to determine the most fuel-efficient approach. Vessels can decrease fuel usage during sailing by avoiding adverse weather conditions such as strong headwinds, rough seas, or harmful currents.

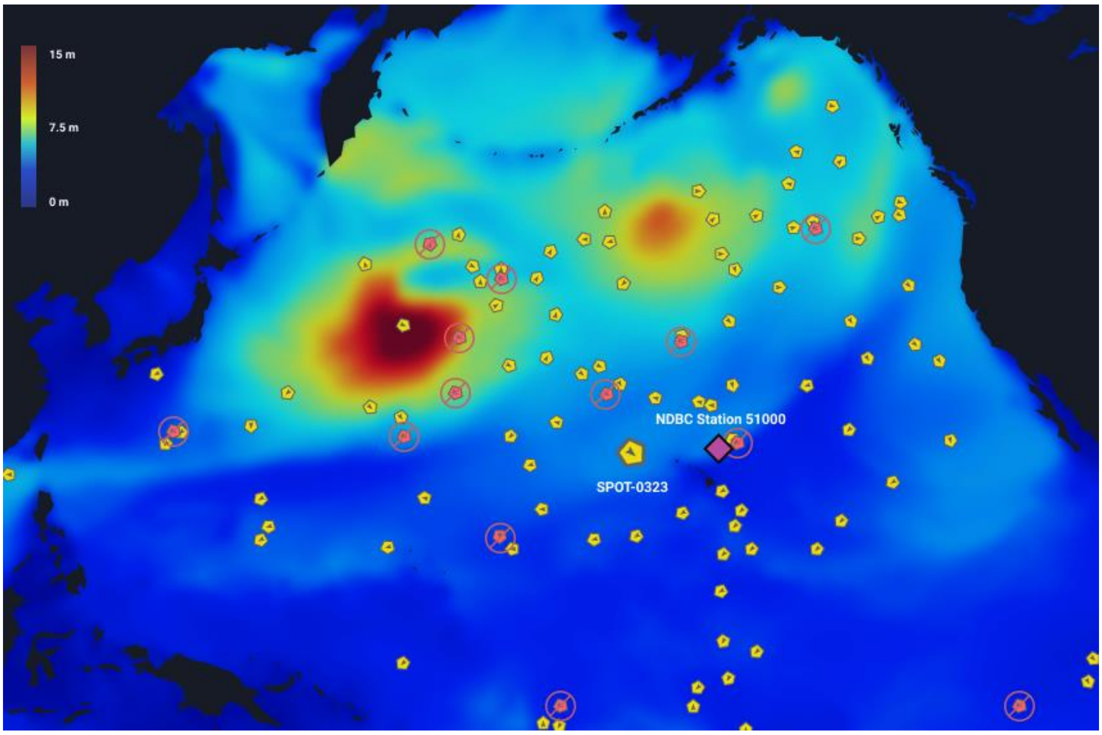
2. Dynamic path steering: Weather conditions at sea are volatile and can rapidly alter. Dynamic climate techniques employ real-time monitoring of climatic conditions and adjust fleet routes to minimise fuel consumption and enhance safety. These systems provide current navigational guidance based on the latest weather forecasts, helping ships manoeuvre seamlessly in changing conditions.

3. Prevent errors (similar to the one involving the Ever Given): Severe weather presents a significant risk to marine operations, and adverse weather conditions are responsible for the absence of several ships. Weather steering services help ships avoid disaster by providing early warnings of hazardous weather conditions and suggesting safe paths to navigate around them.

4. Enhancing margins: Climate initiatives not only result in immediate fuel economic savings but also contribute to improving the profitability of shipping operations. Climate transit systems reduce fuel usage and optimise transit times, resulting in decreased walking costs and improved performance. This can result in reduced insurance premiums, less overtime costs, and fewer delays, leading to significant cost savings and improved profitability.

The extensive network of real-time ocean climate sensors provided by SOFAR Ocean offers vital data to enhance understanding and predictions of ocean conditions. Sofar is able to improve wave forecast models and provide highly precise predictions of wave behaviour by measuring wave conditions, surface winds, and ocean currents in real-time across the Pacific. An illustrative instance of Sofar's tool's effectiveness is its response to a formidable storm that produced winds and waves reaching heights of 30 metres, resulting in substantial coastal damage and impairment of maritime activity. This occurred in the western Pacific region in December 2019.

Figure 7: Weather prediction from Sofar



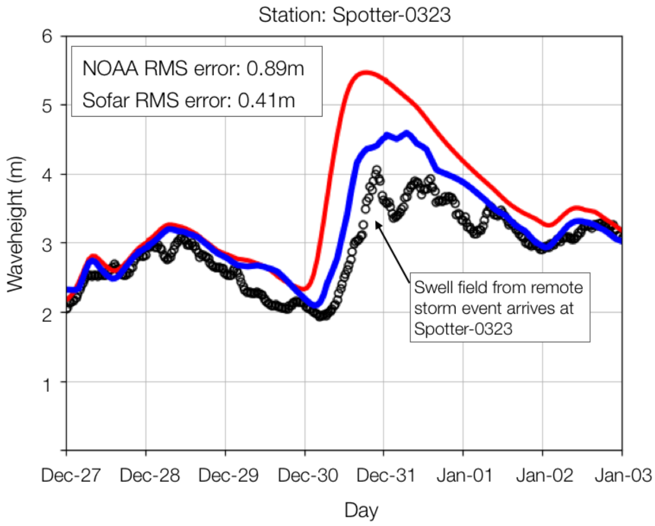
Source: Smit, 2020

Figure 7: Sofar model – weather prediction. The pentagon-shaped icons indicate locations of live Spotter weather buoys currently deployed in the Pacific. The yellow Spotter icons indicate sensors that are used in the data assimilation.

Nevertheless, Sofar's method of utilising data to predict wave patterns provides a resolution. Sofar achieves substantial enhancements in forecast accuracy by incorporating data from its huge sensor network into its global wave forecast model. Sofar's model demonstrated superior performance compared to NOAA's WaveWatchIII model during the December 2019 storm event, resulting in a reduction of root mean square (rms) errors by over 50%.

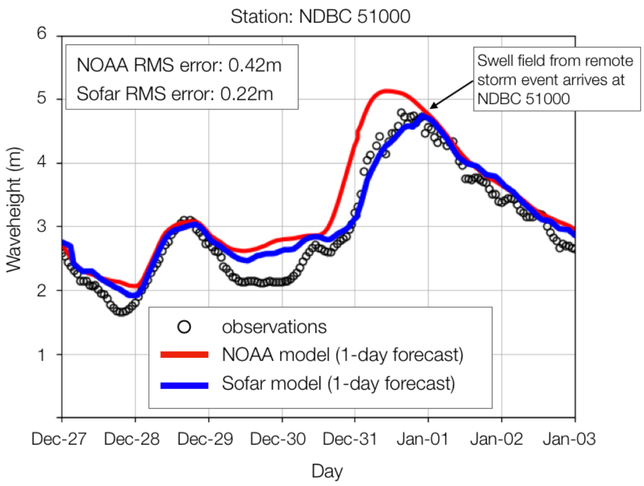
It is crucial to acknowledge that Sofar's model is founded on the same fundamental concepts as NOAA's model. However, the primary distinction resides in the superior quality and amount of data employed for initialising and calibrating the model. The real-time sensor data from Sofar offers a more thorough and precise depiction of ocean conditions, resulting in higher forecast accuracy.

Figure 8: Spotter-0323



Source: Smit, 2020

Figure 9: NDBC 51000



Source: Smit, 2020

Figuree 8 and 9: Comparison of 1-day forecasts to wave height observations at two stations for the arrival of waves radiated by the December 27th storm event (see image 6). Top panel: Spotter-0323. Down panel: NDBC station 51000. These two sites show about 50% reduction in RMS error for both sites. This implies that the data assimilation adds considerable skill to the 24-hr wave forecasts. Refinements in the assimilation strategy will further improve this.

The significance of oceanic climate information cannot be exaggerated, as more than 70% of the Earth's surface is enveloped by water. The ocean surface plays a crucial role in supporting a wide range of economic activities, including maritime transportation, fisheries, aquaculture, marine renewable energy, and business ventures. Furthermore, the interplay between the ocean and the biosphere plays a crucial role in global climate and weather forecasting.

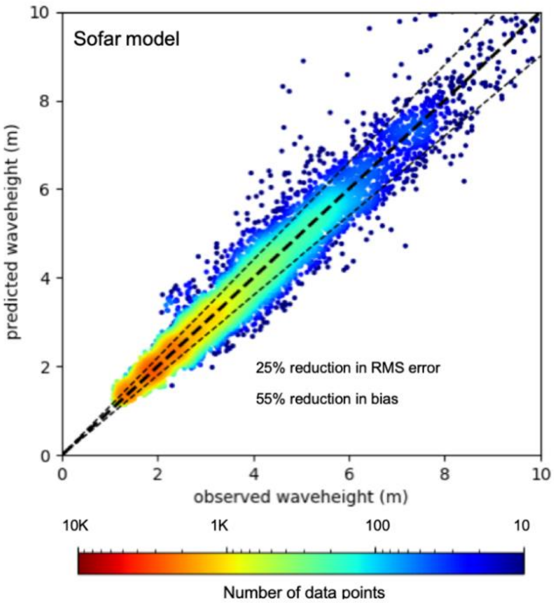
Nevertheless, our understanding of oceanic weather is somewhat restricted, especially in vast open ocean regions where conventional buoy systems are not financially viable. Although coastal buoy networks offer valuable data, their coverage and depth are restricted. When we are in the deepest parts of the ocean, far from the shore, we depend on infrequent visual observations made by ships and measurements taken by satellites. However, these sightings and measurements are often inconsistent and not very accurate. Consequently, several regions around the globe suffer from a notable scarcity of up-to-the-minute oceanic weather data, which has adverse effects on maritime safety and hampers weather prediction endeavours.

Advanced weather models, created by reputable organisations such as NOAA and ECMWF, have significantly enhanced our capacity to predict weather by simulating atmospheric phenomena. Nevertheless, the precision of these models is limited by the calibre and quantity of maritime meteorological data accessible. If the starting state of the ocean in the model is erroneous, the forecast will likewise be inaccurate, following the "garbage in, garbage out" principle.

In order to fill the gap in ocean data, it is necessary to employ novel methods. Conventional single-point sensor systems have limitations in terms of their extent of coverage and capacity to be expanded. Instead, there is a requirement for extensively spread sensor networks comprising of inexpensive nodes to offer unparalleled sensor density throughout expansive oceanic regions. This distributed sensing paradigm entails the deployment of a multitude of sensors throughout the ocean surface to gather real-time data on diverse parameters, including waves, wind, surface drift, and sea surface temperature (SST).

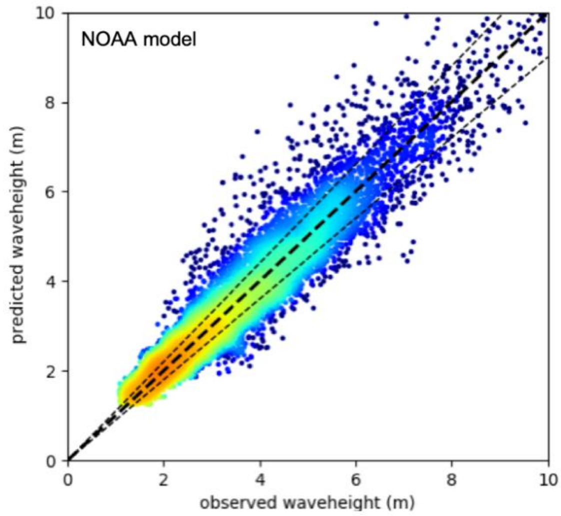
Sofarocean's deployment of 200 Spotter sensors in the Pacific basin is a significant advancement towards achieving this objective. These sensors establish the largest and most advanced privately owned ocean data network in the world. Sofar aims to establish the first worldwide ocean weather sensor network, hence growing its community globally. This initiative will revolutionise our understanding of ocean weather and enhance our forecasting capabilities.

Figure 10: Sodar assimilation model



Source: www.sofarocean.com

Figure 11:NOAA model



Source: www.sofarocean.com

Figure 10 and 11: Scatter plots of modeled vs observed wave height at randomly selected sites in the northern Pacific for the period October 1, 2019, through December 31, 2019. The randomly selected validation sites were not included in the assimilation (see image 6, red-circled Spotters). Figure 10: Sofar assimilation model. Figure 11: NOAA model. The assimilation of the data network into the Sofar model produces a 25% reduction in RMS error across the board, and 50% reduction in model bias

Sofar's data-driven approach to ocean forecasting represents a significant advancement in the field, offering improved accuracy and reliability for critical applications such as coastal protection, maritime safety, and offshore operations.

5.3 A bi-objective weather routing approach

During the last decades, with the huge demand for supplies and services, the shipping factor had to face some very important problems. Time and energy efficiency. The past two decades, with the use of many weather routing systems, this goal has been reached up to one point. The total travel distance has been minimized therefore the fuel consumption and of course the gas emissions. But the problem unfortunately still remains, as the main factor that makes the ship routing problem difficult to solve is the time- varying weather conditions.

According to a study that has been posted by Aphrodite Veneti and her co-workers in 2017, their aim to optimize ship routing by using a time dependent bi0objective shortest path algorithm that simultaneously minimizes fuel consumption and navigational risk. This algorithm will be using a bi-objective formulation which seeks to minimize not only fuel consumption but also risk at the same time. The algorithm will be prioritizes both objectives without compromising one for the other. At the same time, the algorithm will be take into consideration the the weather and sea changes that will be taking place and will be updating its routes suggestions based on real time environmental data. On the other hand, the grid partitioning and pruning techniques that the algorithm is using, create a static grid for fixed geographic data and dynamic grid data (Veneti, 2017)

On the other hand, nowadays there are many methods that are used to optimize weather routing. To begin with, the isochrone method is one of the most used in the shipping factor as it is a classic one, which initially constructs “isochrones” or equal time contours in order to optimize the travel time and reduce fuel consumption by evaluating alterative routes. Another methos is the dynamic programming or DP which breaks down the route into stages and optimizes each decision step by step. This method is communally used for minimizing voyage costs to various weather conditions. Lastly, the calculus of variations is a mathematical approach that calculates optimal routes by adjusting heading and power settings dynamically.

In conclusion, by using weather routing algorithms, studies have shown that the fuel consumption can be reduced by 5%and in many cases it can reach up to 20% with ideal conditions (Thalis, 2020)

CHAPTER 6: CONCLUSIONS

6.1 General considerations

Although weather forecasting devices aim to save fuel and reduce the expected duration of a journey, these are not their intended purposes. Weather forecasting equipment specifically developed for marine operations may be appropriate. For those developing meteorological forecasting gadgets.

Weather routing solutions prioritise the safety of vessels and crew by providing routes that circumvent hazardous weather conditions, such as storms, rough seas, or strong winds. By diverting ships from potentially hazardous situations, these gadgets aid in mitigating the likelihood of accidents and marine mishaps.

Climate forecasting systems aim to decrease overall transportation costs by considering factors such as port taxes, canal tolls, and other expenses associated with certain routes, in addition to saving on petrol prices. Climate transit equipment can further enhance environmental sustainability by mitigating greenhouse gas emissions and curtailing emissions from maritime transport. Weather transport equipment must adhere to laws and norms, such as the Emission Intervention Areas (ECAs) designated by the International Maritime Organisation (IMO). These devices assist transport operators in avoiding penalties and maintaining compliance.

Weather routing technologies improve customer satisfaction by optimising routes to minimise travel time and ensure timely delivery. Complying with transportation timetables and minimising delays boosts the reputation of delivery companies and reinforces customer loyalty.

Climate management solutions have multiple roles beyond only conserving fuel and optimising travel time. They play a crucial role in enhancing security, reducing costs, promoting environmental sustainability, ensuring compliance, and enhancing customer happiness within the maritime industry.

The importance of optimising sea routes for ships is seen in the existing sets of systems, which include the fleet manager and navigator. This tool employs sophisticated time and data analytics to provide optimal solutions that prioritise safety, productivity, and cost-effectiveness.

The strategic planning process must take into account several elements, such as the kind and duration of vessels, cargo capacity and sensitivity, load circumstances, environmental conditions, adherence to legal requirements and environmental rules, and objectives.Furthermore, the incorporation of worldwide weather prediction into road design systems allows for proactive decision-making and immediate modifications to enhance road quality in response to fluctuating weather conditions.

Another crucial aspect of the navigation planning process is the determination of the captain's role and the categorisation of the observer. Although route planners offer standardised itineraries, ultimately the captain makes definitive decisions based on real-time conditions and operational limitations. Moreover, delivery managers have a crucial function in managing cargo handling and storage facilities, as well as overseeing supply and bunkering operations, in order to enhance the efficiency of overall transportation systems.

In summary, the integration of top-notch generation, verification of information, and human comprehension in navigation systems like Optinav signifies a significant advancement in the maritime sector. These gears enhance not only efficiency and tax payments, but also safety, environmental sustainability, and patron pride in the transport firm. Utilising groundbreaking technology such as Optinav may be essential in order to avoid.

References

- Al-Enazi, A., Okonkwo, E. C., Bicer, Y., & Al-Ansari, T. (2021). A review of cleaner alternative fuels for maritime transportation. *Energy Reports*, *7*, 1962-1985.
- Anwar, Syed Tariq,2020, "Global strategy gone astray: Maersk's big box boats and the world shipping industry." *Thunderbird International Business Review*
- Bayraktar, Murat, and Onur Yuksel, 2023, "A scenario-based assessment of the energy efficiency existing ship index (EEXI) and carbon intensity indicator (CII) regulations." *Ocean Engineering*
- Bertram, V., & Schneekluth, H. (1998). *Ship design for efficiency and economy*. Elsevier.
- Brynolf, S., Fridell, E., & Andersson, K. (2014). Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. *Journal of cleaner production*, *74*, 86-95.
- Chaal, M. (2018). Ship operational performance modelling for voyage optimization through fuel consumption minimization.
- Crawford, E. (1997). Arrhenius' 1896 model of the greenhouse effect in context. *AMBIO-STOCKHOLM-*, *26*, 6-11.
- Dikshit, S., Atiq, A., Shahid, M., Dwivedi, V., & Thusu, A. (2023). The use of artificial intelligence to optimize the routing of vehicles and reduce traffic congestion in urban areas. *EAI Endorsed Transactions on Energy Web*, *10*.
- Donepudi, Praveen Kumar. "Technology growth in shipping industry: an overview." *American Journal of Trade and Policy*, 2014
- Forwarder Magazine "The Importance of Weather Routing in Fuel-Efficient Shipping"
- Garcia, Beatriz, Anita Foerster, and Jolene Lin, 2021, "Net zero for the international shipping sector? An Analysis of the Implementation and Regulatory Challenges of the IMO Strategy on Reduction of GHG Emissions." *Journal of Environmental Law*
- Gibson, H. L., Allen, R. L., Riverin, G., & Lane, T. E. (2007, September). The VMS model: Advances and application to exploration targeting. In *Proceedings of Exploration* (Vol. 7, pp. 713-730).
- Gibson, H. L., Allen, R. L., Riverin, G., & Lane, T. E. (2007, September). The VMS model: Advances and application to exploration targeting. In *Proceedings of Exploration* (Vol. 7, pp. 713-730).
- Glomeep,Global Maritime energy efficiency partnership, “Weather Routing”
- Grifoll, M., Borén, C., & Castells-Sanabra, M. (2022). A comprehensive ship weather routing system using CMEMS products and A* algorithm. *Ocean Engineering*, *255*, 111427.

- Hansen, E. K., Rasmussen, H. B., & Lützen, M. (2020). Making shipping more carbon-friendly? Exploring ship energy efficiency management plans in legislation and practice. *Energy Research & Social Science*, *65*, 101459.
- Harati-Mokhtari, A., Wall, A., Brooks, P., & Wang, J. (2007). Automatic Identification System (AIS): data reliability and human error implications. *the Journal of Navigation*, *60*(3), 373-389.
- Harati-Mokhtari, A., Wall, A., Brooks, P., & Wang, J. (2007). Automatic Identification System (AIS): data reliability and human error implications. *the Journal of Navigation*, *60*(3), 373-389.
- Hashali, S. D., Yang, S., & Xiang, X. (2024). Route Planning Algorithms for Unmanned Surface Vehicles (USVs): A Comprehensive Analysis. *Journal of Marine Science and Engineering*, *12*(3), 382.
- How, M. L., Cheah, S. M., Khor, A. C., & Chan, Y. J. (2020). Artificial intelligence-enhanced predictive insights for advancing financial inclusion: A human-centric ai-thinking approach. *Big Data and Cognitive Computing*, *4*(2), 8.
- IMO, S. C. E. (2018). IMO.
- Karin Andersson, Selma Brynolf, Fredrik Lindgren, Magda Wilewska-Bien
- Karin Andersson, Selma Brynolf, J. Fredrik Lindgren, Magda Wilewska-Bien, "Shipping and the Environment, Publisher Springer, 2016,
- Kass, M., Kaul, B., Armstrong, B., Szybist, J., & Lobodin, V. (2022). Stability, rheological and combustion properties of biodiesel blends with a very-low sulfur fuel oil (VLSFO). *Fuel*, *316*, 123365.
- Kumari, S. (2021). Interplay of AI-Driven Maritime Logistics: An In-Depth Research into Port Management, Advanced Operations Automation, and CRM Integration for Optimized Performance and Efficiency. *ESP Journal of Engineering and Technology Advancements*, *1*(1), 1-5.
- La Ferlita, A., Qi, Y., Di Nardo, E., el Moctar, O., Schellin, T. E., & Ciaramella, A. (2023). A comparative study to estimate fuel consumption: a simplified physical approach against a data-driven model. *Journal of Marine Science and Engineering*, *11*(4), 850.
- Lipkova, J., Chen, R. J., Chen, B., Lu, M. Y., Barbieri, M., Shao, D., ... & Mahmood, F. (2022). Artificial intelligence for multimodal data integration in oncology. *Cancer cell*, *40*(10), 1095-1110.
- Marine Digital, 2013, https://marine-digital.com/article_eeoi
- Mark Cartwright, 2020, "Trade & Commerce in Ancient Greece"
- Max Baehr, 2022, "Air Freight vs. Sea Freight"
- Nikolaos Christopoulos, Dimitrios V. Lyridis, Panayiotis Mitrou, Christos Papaleonidas, Panayiotis Evangelou. "Quantitative Analysis of the Global Commercial Fleet GHG Emissions Profile", NTUA SNAME Laboratory for Maritime Transport Feb. 2019

- Parker, T. (2022). Atmospheric CO2 at Mauna Loa Observatory. NOAA Climate.
- R.N Colvile, E.J Hutchinson [1 a], J.S Mindell [b], R.F Warren , 2001, “The transport sector as a source of air pollution”
- Riyadh, M. (2024). Transforming the Shipping Industry with Autonomous Ships and Artificial Intelligence. *Maritime Park: Journal of Maritime Technology and Society*, 81-86.
- Sang-Su Lee, 2024, “Analysis of the effects of EEDI and EEXI implementation on CO_2 emissions reduction in ships”
- Sidhu, H. K. (2020). *Performance Evaluation of Pathfinding Algorithms* (Master's thesis, University of Windsor (Canada)).
- Smit, P. B., Houghton, I. A., Jordanova, K., Portwood, T., Shapiro, E., Clark, D., ... & Janssen, T. T. (2020). Assimilation of distributed ocean wave sensors. *arXiv preprint arXiv:2003.04435*.
- Taskar, B., & Andersen, P. (2020). Benefit of speed reduction for ships in different weather conditions. *Transportation Research Part D: Transport and Environment*, *85*, 102337.
- The Economist 2015, Low Rates on High Seas, viewed April 1, 2015
- Tien, J. M. (2017). Internet of things, real-time decision making, and artificial intelligence. *Annals of Data Science*, *4*, 149-178.
- Tran, T. A. (2017). A research on the energy efficiency operational indicator EEOI calculation tool on M/V NSU JUSTICE of VINIC transportation company, Vietnam. *Journal of Ocean Engineering and Science*, *2*(1), 55-60.
- Veneti, A., Makrygiorgos, A., Konstantopoulos, C., Pantziou, G., & Vetsikas, I. A. (2017). Minimizing the fuel consumption and the risk in maritime transportation: A bi-objective weather routing approach. *Computers & Operations Research*, *88*, 220-236.
- Verma, B. K. (2009). Long range identification and tracking (LRIT) apropos global maritime security. *Maritime Affairs: Journal of the National Maritime Foundation of India*, *5*(1), 39-56.

- Verma, B. K. (2009). Long range identification and tracking (LRIT) apropos global maritime security. *Maritime Affairs: Journal of the National Maritime Foundation of India*, *5*(1), 39-56.

- William Conroy, 2019, “Exploring the Impact of Greek Colonization and trade”