RESEARCH, TECHNOLOGY AND INNOVATION IN SHIPBUILDING AND MARITIME

EDITORS
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PREFACE

The maritime industry, as the principal driving force of global trade, plays a vital role in ensuring the sustainability of the world economy. In this context, the reduction of environmental impacts, the enhancement of energy efficiency, the optimization of production processes, and the implementation of technological innovations have become central focal points of contemporary naval architecture and marine engineering studies.

As the Faculty of Naval Architecture and Maritime at İzmir Kâtip Çelebi University, we have embraced the mission of cultivating qualified, innovative, and responsible engineers who will contribute to the advancement of the maritime and shipbuilding industries. In line with this mission, we attach great importance to disseminating both our academic knowledge and practical experience through scientific publications that bridge the gap between research and industry.

This book encompasses fundamental and contemporary topics in naval architecture and marine engineering, including air and water pollution from ships, energy efficiency, ship production facilities and methods, life-cycle assessment, autonomous ship operations, education in naval architecture, and ship hydrodynamics. Each chapter has been meticulously prepared by distinguished scholars in their respective fields, aiming to provide both the academic community and the maritime sector with current, applicable, and insightful knowledge.

We believe that this book will advance environmental sustainability, technological innovation, and the scope of education within the field of naval architecture and marine engineering. With sincere appreciation for all faculty members and contributors whose dedication made this work possible, we reaffirm our commitment to the continued creation and sharing of scientific knowledge that will further the progress of maritime studies both nationally and internationally.

November 10, 2025

Editors, Asst. Prof. Dr. Koray SAHIN, Asst. Prof. Dr. Caglar DERE

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CHAPTER 1

REGULATED AND NON-REGULATED ASPECTS OF SHIP EMISSIONS: LEGISLATION, IMPACTS AND FUTURE PERSPECTIVES

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Abstract

The topic of regulated and non-regulated emissions on ships is a highly relevant and valuable topic in maritime engineering, environmental sciences, sustainable transportation, and energy technologies. Environmental regulations that came into force within the scope of MARPOL, IMO's 2020 sulfur limit policy, energy efficiency indices (EEDI, EEXI, CII) and developments in alternative fuel technologies (LNG, methanol, ammonia, hydrogen, etc.) have led to a significant increase in interest in this field recently. This section comprehensively examines the environmental impacts of the maritime transport sector through ship emissions, examining the differences between regulated emissions (SO_X, NO_X, CO_2, and PM) and non-regulated emissions (black carbon, methane, ammonia slip, nitrous oxide, metal particles, and volatile organic compounds), the current regulatory framework, and future policy perspectives from a holistic perspective. Global limit values and energy efficiency indicators have been determined for the regulated pollutants SO_X, NO_X, CO_2, and PM. In contrast, non-regulated emissions, such as black carbon, methane, ammonia, and metal particles, which have not yet been fully incorporated into legislation, represent future environmental risks. Progress on regulated emissions must be complemented by controlling non-regulated pollutants. Legislation must be supported by technological innovation, and financing must be embedded within a fair framework that prioritizes environmental integrity. Ultimately, a sustainable maritime future is possible through effective regulatory enforcement, innovative technologies, equitable policies, and international cooperation.

Keywords: ship emissions, regulated emissions, non-regulated emissions, alternative fuels, maritime legislation, green fuels.

1. Introduction

Maritime transportation is the most fundamental logistics element, accounting for approximately 90% of the global trade in volume today. According to Clarkson Research, while the amount of cargo carried in maritime transport exceeded 12 billion tons in 2024, trade volume increased by 2.2% compared to 2023 (UNCTAD, 2025). The majority of strategic goods such as crude oil, coal, grain, containerized goods, and liquefied natural gas (LNG) move by sea transport. This has made maritime transportation not only a logistics sector but also the backbone of global economic stability. This strategic sector with such a large volume is also a significant environmental pressure factor. Air emissions released from ships negatively affect the global climate balance and endanger the health of people living in ports and coastal areas by reducing regional air quality.

IMO data shows that ship-related CO_2 emissions account for approximately 2.89% of the global total, and a growth in the sector brings with it a steady increase in this share (IMO GHG Study, 2020).

Ship-related air emissions consist of gaseous and particulate compounds released into the atmosphere whenever the ship burns fuel or produces energy. These compounds differ from each other in terms of their environmental effects, toxic properties, and atmospheric residence time. International regulations currently in force require both limitation and monitoring and reporting for certain emission components. These are often referred to as regulated emissions and include components such as NO_x, SO_x, CO, CO_2, and PM (IMO MARPOL Annex VI, 2005). For these pollutants, whose effects on the environment have long been known, international limit values and control zones (IMO ECA Annex 11, 2010; IMO ECA Annex 14, 2011) have been established and implemented.

In contrast, a group of pollutants defined as non-regulated emissions are not yet covered by current international or regional standards. Methane (CH_4), black carbon (BC), nitrous oxide (N_2O), ammonia (NH_3), and volatile organic compounds (VOCs) are among the most prominent components of this group. Significant uncertainties remain in measuring, modeling, and regulating these emissions (Suarez-Bertoa et al., 2020). For example, the "methane slip" phenomenon observed in LNG-fueled ships stands out as a new environmental issue that limits the expected climate benefits of low-carbon fuels.

From this perspective, assessing ship emissions solely on the basis of the components regulated by legislation carries the risk of causing significant gaps in environmental impact analyses. In reality, the maritime sector is a complex system requiring the holistic management of all emissions, both regulated and non-regulated. This chapter examines these two emission categories from a technical, environmental, and legal perspective, providing a comprehensive assessment of current regulations, measurement methods, and future policy trends. It aims to contribute to a holistic approach to emission management within the sustainable transformation of maritime transport.

2. Ship Emissions Typology

Variations in the type, magnitude, and environmental impact of ship-generated emissions are influenced by fuel characteristics, engine technology, operational conditions, and the application of emission control measures (Jiaqiang et al., 2017; Hurren et al., 2025). Ship emissions are generally classified into two main groups: regulated and non-regulated. This classification is based on whether the emissions are subject to any international or regional regulations.

2.1. Regulated emissions

Regulated emissions are pollutants subject to limit values and control mechanisms set by international maritime authorities. There is a need to regularly measure, report and limit these emissions. The most basic regulatory framework is contained in Annex VI of the IMO's MARPOL 73/78 Convention, which contains provisions on the prevention of air pollution (IMO MARPOL Annex VI, 2021). The main types of regulated emissions are summarized below:

Nitrogen oxides (NO_x): NO_x are one of the most important pollutants formed in ship engines and other combustion systems. The term "NO_x" generally refers to the sum of nitrogen monoxide (NO) and nitrogen dioxide (NO_2) gases. Both are formed when the nitrogen content of the fuel or air reacts with oxygen at high temperatures. Nitrogen oxides (especially NO and NO_2) undergo various chemical reactions after being emitted into the atmosphere, forming different air pollutants and secondary compounds. The categories and impacts of the secondary compounds, as well as their effects on human health and the environment, are shown in Table 1 (Boningari & Smirniotis, 2016).

Table 1. Impacts of nitrogen oxides on environmental quality and human health.

Secondary Compounds/Effect	Process	Result
Ozone (O_3)	The photochemical reaction (NO_x+ VOCs+ sunlight)	Photochemical smog, health problems
Nitric Acid (HNO_3)	NO_2+$H_2$0 reaction	Acid rain
Secondary Particulate Matter ($PM_{2.5}$)	NO_x +NH_3+SO_2 reaction	Respiratory problems, fog
Nitrate accumulation	Transported to the Earth by precipitation	Soil/water pollution and eutrophication
Tropospheric ozone increase	Photochemical process	Greenhouse effect, plant damage

For nitrogen oxides, three different levels (Tier I, Tier II and Tier III) limit values are defined depending on the engine power and speed (IMO NO_x Technical Code, 2008).

Sulfur oxides (SO_X): Fossil fuels such as heavy fuel oil (HFO) and marine gas oil (MGO) used in ships contain a certain amount of sulfur. During fuel combustion, this sulfur combines with oxygen to form SO_2 gas. SO_x formation depends largely on the sulfur content of the fuel, but the combustion temperature and oxygen content also play a role. The environmental and health effects (Corbett et al., 2016) of SO_x are listed in Table 2.

Table 2. Effects of sulfur oxides on human health and the environment.

Area of Influence	Explanation	Results/Examples
Air Quality	SO_2 is present in the atmosphere as sulfur dioxide gas.	Acidification of the air, haze, reduced visibility.
Acid Rain	SO_2 reacts with water vapor and oxygen to form sulfurous acid (H_2SO_4).	Acidification of the soil and water ecosystems, damage to vegetation, corrosion of buildings and metal structures.
Particulate Matter Formation	SO_2 in the air can react with ammonia and various gases, contributing to the formation of sulfate particles.	$PM_{2.5}$ and PM_{10} formation, they penetrate deep into the lungs, posing cardiovascular and respiratory health risks.
Human Health (Respiratory)	SO_2 causes irritation to the lungs and respiratory tract when inhaled.	Asthma, bronchitis, respiratory tract irritation, and chronic respiratory diseases
Ecosystems and Agriculture	Plant and aquatic life are affected as a result of soil and water acidification.	Yield loss, biodiversity reduction, eutrophication risk
Impact on the Climate	Sulfate aerosols can reflect sunlight and provide a short-term cooling effect.	Local climate changes, weather patterns, complex long-term climate impacts

The global sulphur limit set by IMO has been implemented as % 0.50 as of 2020; this limit is 0.10% in Emission Control Areas (IMO MARPOL ANNEX VI Sulphur Limit, 2020).

Carbon Monoxide (CO): Incomplete combustion of the fuel leads to the formation of this component. The CO level is directly affected by the combustion conditions and engine operating characteristics, particularly the combustion temperature, oxygen content, fuel quality and engine load. The environmental and health effects (US-EPA, 2009),(WHO, 2021) of CO are listed in Table 3.

Carbon dioxide (CO_2): Approximately 2.89% of the greenhouse gas emissions produced worldwide are released by the maritime transport sector (IMO GHG Study, 2020). CO_2 is the most significant direct contributor to climate change and is therefore indirectly regulated through energy efficiency indicators (EEDI, EEXI, CII).

Table 3. Impacts of carbon monoxide on environmental quality and human health.

Area of Influence	Explanation
Air Quality	CO contributes to local air pollution, especially in port cities.
Human Health	CO blocks oxygen transport both when inhaled and through the blood (dizziness, fatigue, and severe poisoning)
Ecosystems	Atmospheric CO can influence tropospheric ozone formation by participating in some photochemical reactions.

IMO has developed a three-dimensional approach to reducing CO_2 emissions through design (EEDI-Energy Efficiency Design Index), operational performance (CII-Carbon Intensity Indicator), and improvements to existing ships (EEXI-Energy Efficiency Existing Ship Index). These mechanisms aim to reduce CO_2 emissions per tonne-km and make maritime transport more sustainable. The overall impact and importance of these mechanisms are described in Table 4.

Table 4. The overall impact and importance of the energy efficiency indicators.

Mechanism	Purpose	Application Area	Impact
EEDI	Energy efficiency in the new ship design	Newbuilding ships	Reduces CO_2 emissions at the design stage
CII	Operational CO_2 intensity monitoring	Existing and new ships	The ship's annual CO_2 intensity is measured and classified
EEXI	Design-based energy efficiency of existing ships	Existing ships	CO_2 reduction is achieved in older ships, and compliance with IMO standards is mandatory

Global warming, climate change and ecosystem degradation caused by CO_2 have serious consequences for human health and the environment. The environmental and health effects (Jacobson et al., 2019) of CO_2 are listed in Table 5.

Particulate matter (PM): Ship-borne PM is primarily formed due to fuel combustion, fuel composition, and engine combustion inefficiency. PM is a substance suspended in the atmosphere as solid or liquid particles.

Table 5. Impacts of carbon dioxide on environmental quality and human health.

Area of Influence	Explanation	Results/Examples
Indirect Effects on Air Quality	Although CO_2 is not toxic on its own, it can affect the formation of ozone and smog because of atmospheric changes.	Increase in asthma and other respiratory diseases
Climate Change	Carbon dioxide serves as a greenhouse gas in the atmosphere, thereby contributing to the rise in the Earth's surface temperatures.	Rising global temperatures, increasing sea levels, and severe weather events such as hurricanes, droughts, and floods
Ecosystems	Changes in temperature and ocean chemistry disrupt the ecosystem balance.	Migration or extinction of species, and loss of biodiversity
Sea Level Rise	Melting of glaciers and expansion of the sea	Flood risk, migration and economic losses in coastal cities
Indirect Human Health Effects	While CO_2 is not directly toxic, it increases health risks through climate change.	Deaths due to heat stress, waterborne diseases, food safety issues, and respiratory problems due to air quality deterioration

It dissolves into the air as both visible soot and ultrafine particles, creating serious health and environmental impacts. It is generally classified as PM_{10} (diameter < 10 µm) and $PM_{2.5}$ (diameter < 2.5 µm). NO_x and SO_x gases can form sulfate and nitrate particles (secondary PM) in the atmosphere. This process is a significant contributor to $PM_{2.5}$ formations. The environmental and health effects (Anderson et al., 2012) of PM are summarized in Table 6.

Table 6. Impacts of PM on environmental quality and human health.

Area of Influence	Explanation
Air Quality	Visible soot and haze formation, reduced visibility
Human Health	$PM_{2.5}$ reaches the lungs (asthma, bronchitis, and cardiovascular diseases)
Ecosystems	It affects the ecosystem and plant health by settling on the soil and water surface.
Impact on the Climate	Black carbon particles absorb sunlight (local warming and glacial melting)

These types of emissions are limited by internationally defined limits and are subject to monitoring obligations. However, this framework is not sufficient to cover all the pollutants emitted from ships; some new-generation compounds are still excluded from the current regulations.

2.2. Non-regulated emissions

Today, most ship-related air emissions are controlled by various international regulations and standards. However, the combustion process in ship engines not only produces SOx, NOx, and CO_2; a range of less prominent gases and particulates, which may pose risks to both the environment and human health, are emitted into the atmosphere. Some of these compounds are not yet considered within the scope of international regulations. However, studies have revealed that these compounds can have serious consequences for the climate and human health (Duan et al., 2024). Therefore, the topic of "non-regulated emissions" is becoming increasingly important for future environmental policies. The main types of non-regulated emissions are:

Methane (CH_4): Methane occurs when unburned methane gas leaks into the atmosphere from LNG-fueled ships. This phenomenon, known as "methane slip" reduces LNG's advantage as a low-carbon fuel and has an impact approximately 28 times that of CO_2 in terms of its 100-year global warming potential (IPCC, 2023). For this reason, the IMO and the scientific community are paying special attention to the “methane slip” problem and are working on technologies to reduce methane emissions in LNG engines. Although methane itself is not toxic, it significantly affects both climate and human health through its greenhouse properties and contribution to secondary air pollutants such as ozone. Therefore, it is one of the major gases expected to be included in the IMO's non-regulated emissions scope in the future.

Ammonia (NH_3): In new generation ammonia-fueled engines or Selective Catalytic Reduction (SCR) systems, it can mix with the atmosphere in the form of “ammonia slip”. It may cause effects such as respiratory tract irritation and ecosystem acidification.

Black carbon (BC): BC is made up of tiny carbon particles formed when the fuel burns incompletely. It forms particularly in ships using heavy fuel oil due to its low combustion efficiency. In other words, the inability to oxidize carbon to CO_2 releases of black carbon in the form of soot. The combustion of the fuel and the formation of BC is shown in equation 1.

$$C_xH_y + O_2 \rightarrow CO_2 + H_2O + BC(soot) \quad (1)$$

The IMO is currently conducting technical studies to define and measure black carbon.

Azote protoksit (N_2O): It can be formed as a by-product in NO_x reduction systems (e.g., SCR) and alternative fuel combustion. It is a strong greenhouse gas due to its long atmospheric life.

Volatile organic compounds (VOCs): VOCs, which are composed of carbon, can evaporate quickly under standard ambient conditions. It contributes to the photochemical ozone formation. Ship-related VOC emissions arise from three main processes:

- *Fuel evaporation:* It forms in ship storage tanks, particularly during the loading, unloading, or transportation of crude oil and petroleum products. Hydrocarbons (e.g., benzene, toluene, ethylene, and xylene) evaporate from the surface of the fuel and are released into the atmosphere.
- *Loading and ventilation operations:* VOCs are released into the atmosphere during the ventilation process called “tank breathing” on crude oil tankers.
- *Combustion process:* When complete combustion does not occur in diesel engines, hydrocarbons in the fuel partially burn to form VOCs.

VOC emissions are partially regulated for tankers transporting crude oil (IMO MARPOL ANNEX VI Regulation 15, 1996). The use of control systems (e.g., VOC recovery units) is recommended. However, there are no binding limits for other ship types (e.g., LNG carriers, cruise ships). Therefore, VOCs are still considered to be limited in scope and partially regulated emissions.

Metal particles: The release of trace metals (vanadium, nickel, etc.) into the atmosphere occurs due to engine wear and fuel additives, creating adverse effects on marine and human health. The importance of many of these pollutants is rising, particularly with the adoption of low-carbon or alternative fuels. For example, it is anticipated that nitrogenous compounds and NH_3 leaks may increase in ammonia- and hydrogen-fueled systems (Chavando et al., 2024). Therefore, future maritime policies will need to be expanded to cover not only traditional pollutants but also these "next-generation" emissions.

Consequently, classifying ship emissions as regulated and non-regulated is not merely a technical distinction but also a strategic framework that determines the regulatory scope and research priorities. While existing control systems and limits for regulated emissions are becoming increasingly stringent, the lack of scientific data for non-regulated components hinders policy development. Therefore, effective emission management in the maritime sector requires a combined assessment of both categories and the expansion of measurement and reporting standards.

3. Regulated Emissions and The Regulatory Framework

The environmental and health impacts of emissions from maritime transport have long been recognized. Therefore, since the late 20th century, international maritime authorities have developed comprehensive regulations to control pollutants from ships. The regulated emissions consist of pollutants with legally established limit values, monitoring requirements, and compliance mechanisms. This section examines the technical and policy aspects of regulating these emissions and the associated legislative framework.

3.1 International regulations

3.1.1 MARPOL Annex VI: IMO's role in international shipping

The most comprehensive international legal basis for reducing air pollution from maritime shipping is defined in Annex VI of the 73/78 MARPOL Convention. This Annex, adopted in 1997 and entered into force in 2005, aims to reduce the emissions of polluting gases such as SO_x, NO_x, CO, CO_2 and PM (IMO, 1978).

The main components of Annex VI are as follows:

Sulfur oxide (SO_x) Limits: A global restriction on the sulfur level in ship fuels has been implemented by the IMO. Effective from January 1, 2020, the regulation stipulates that the sulfur level in ship fuels must not exceed 0.50%. However, this limit is applied at 0.10% in areas designated as ECA. These areas include the Baltic Sea, the North Sea, North American coastal waters (IMO ECA Annex 11, 2010), and the US Caribbean (IMO ECA Annex 14, 2011).

Nitrogen oxides (NO_x): Limits for NOx emissions are implemented within a three-tiered system (Tiers I–III), determined by the engine type and production date. At Tier III, ships built after 2016 require an 80% nitrogen oxide reduction in selected ECA zones (IMO NOx Technical Code, 2008).

Energy efficiency standards: The Energy Efficiency Design Index (EEDI), incorporated into MARPOL Annex VI in 2011, is a mandatory indicator that assesses the energy performance of new ships (IMO MARPOL EEDI, 2011). Subsequently, the Existing Ship Energy Efficiency Index (EEXI) and the Carbon Intensity Indicator (CII) were also incorporated into this system. These indicators contribute to low-carbon maritime goals by reducing CO_2 emissions from ships' operational activities (DNV, 2025).

Fuel quality and certification: In this context, ships are required to have a Bunker Delivery Note (BDN) document showing the sulfur content of the fuel they use. Ships equipped with scrubber systems are regularly inspected for compliance with the approved performance criteria defined by the IMO. These regulations are mandatory for all ships engaged in international voyages and are supported by the IMO's current technical framework. In addition, some regional authorities have developed additional practices that further tighten these standards.

3.2 Regional regulations

3.2.1 The European Union (EU) approach

The European Union has gone beyond IMO standards and adopted stricter practices on a regional basis.

MRV Regulation: Regulation 2015/757 of the European Union has created an obligation for ships to monitor, report and verify their CO_2 emissions. This system is mandatory for ships over 5,000 GT and has been in force since 2018.

EU ETS (Emissions Trading System): As of 2024, the maritime transport sector will be included in the ETS. This obligation includes purchasing carbon credits for a certain percentage of CO_2 emissions from ships (European Commission, 2024). This system has been established to place an economic value on carbon emissions in maritime transport.

FuelEU Maritime: This regulation, scheduled to come into effect in 2025, aims to limit the carbon intensity of marine fuels. Efforts also focus on boosting the deployment of low-carbon fuel options such as biofuels, ammonia, and e-fuels.

3.2.2 US and other country applications

The United States actively monitors SO_X and NO_X emission limits in the North American ECA region, designated under MARPOL Annex VI. China implemented the Domestic Emission Control Area (DECA) in coastal areas in 2019, reducing fuel sulfur from 0.5% to 0.10%. Japan, South Korea, and Australia have also implemented similar national fuel standards (CCAC, 2016).

This demonstrates the existence of a multi-layered regulatory system in maritime transport: IMO global standards provide the basic framework, while regional and national practices strengthen environmental protection.

3.3 Compliance, Auditing and Sanctions

Effective control of regulated emissions is possible not only through the establishment of technical limits but also through the effective implementation of compliance and control mechanisms. In this context, two main levels of control stand out:

Flag State Control: The state in which the ships are registered is responsible for ensuring that the ships in its fleet comply with the provisions of MARPOL Annex VI.

Port State Control: Foreign-flagged vessels calling at the port are inspected. Fuel samples are taken, certificates are reviewed, and non-compliance may result in fines or a ban on navigation. Compliance requires that ships carry specific technical certificates and plans, including the IAPP (International Air Pollution Prevention Certificate), SEEMP (Ship Energy Efficiency Management Plan), and the EIAPP (Engine International Air Pollution Prevention Certificate). These documents confirm that the ship complies with the established emission limits and has implemented appropriate energy management plans.

3.4 Assessment: The evolution of regulated emissions management

A considerable reduction in air pollution from maritime transport has been achieved due to the regulations implemented by the IMO and regional authorities over the past 20 years. For example, SO_x levels have fallen by more than 70% in the Baltic and North Sea ECA regions, while the widespread adoption of Tier III engines has also led to a significant reduction in NO_x emissions (EMSA, 2025).

Looking ahead, the IMO's carbon neutrality target for 2050 will necessitate the expansion of existing regulations and the implementation of more stringent standards for greenhouse gas emissions. Furthermore, the inclusion of currently non-regulated compounds such as BC and CH_4 is an essential requirement for the integrity of emission management.

4. Non-Regulated Emissions: New Threats

Since the mid-20th century, the maritime transportation sector has undergone a structural transformation under the influence of technological developments. This process has led to an increased diversity in fuel types, engine technologies, and emission control systems. However, some compounds beyond the pollutants currently focused on by legislation (SO_x, NO_x, CO_2, PM) and not yet adequately regulated are becoming increasingly important from an environmental perspective. These compounds, referred to as "non-regulated emissions," pose new risks to both the climate system and human health.

This section discusses the main types of non-regulated emissions, their environmental impacts, and the potential for future regulation.

Black Carbon (BC): BC is a compound composed of unburned or partially burned carbon particles that strongly absorb optical light. It forms in ship engines, particularly during the incomplete combustion of HFO. Although black carbon has a short lifespan (SLCPs) in the atmosphere (days to weeks), its impact on sensitive ecosystems such as the Arctic is extremely high (Saxena & Chandra, 2011).

When BC particles settle on snow and ice surfaces, they reduce the albedo of these surfaces, causing them to absorb more sunlight. This accelerates regional warming and triggers melting processes. BC emissions from ships operating in the Arctic increased by 114% between 2015 and 2021 (Osipova & Gore, 2025).

The IMO is conducting research on the identification, measurement, and reduction of black carbon and is developing a Black Carbon Measurement Protocol. However, the compound is not currently included in MARPOL Annex VI. Therefore, black carbon is considered the most critical "non-regulated" pollutant from a climatic perspective in the maritime sector.

4.2. Methane (CH_4): LNG's climate-related sustainability problem

Although CH_4 has a shorter lifetime in the atmosphere than CO_2, its global warming effect over a century is 28 times that of CO_2 (UNECE, 2021) The shift toward LNG to reduce greenhouse gases in maritime transport has led to the emergence of methane emissions as a new environmental challenge.

Methane that cannot be fully oxidized in the engine combustion chamber leaks into the atmosphere through the exhaust as methane slips. These losses vary depending on the engine type but can reach approximately % 1–3 of the total fuel consumption (DNV, 2025). As a result, LNG's low-carbon fuel advantage is significantly reduced, and in some scenarios, its carbon footprint approaches conventional fuel levels.

4.3 Nitrous oxide (N_2O) and Ammonia (NH_3)

New generation nitrogenous fuels and SCR systems can cause N_2O and NH_3 gases to be released into the atmosphere as by-products.

Nitrous oxide (N_2O): SCR systems used in NO_x reduction technologies can lead to the production of N_2O due to side reactions. N_2O is a greenhouse gas 265 times more potent than CO_2 and can persist in the atmosphere for 120 years or more (Yao et al., 2022).

Ammonia (NH_3): In the future, ammonia-based fuels (e.g., "green ammonia") will be used as alternative energy sources. However, unburned ammonia can leak into the atmosphere ("ammonia slip") due to engines or SCR systems, posing environmental and health risks. NH_3 irritates the respiratory tract and can lead to acidification and nitrification, causing toxic effects in marine ecosystems.

Therefore, ammonia and N_2O emissions are gaining importance as new areas of regulation and monitoring in future fuel conversion scenarios. The IMO and ISO are developing life cycle-based emission calculation guidelines for these gases.

4.4 Volatile organic compounds (VOCs)

In tankers carrying crude oil and petroleum products, VOC emissions enter the atmosphere through evaporation during loading and unloading. These gases significantly contribute to the development of ozone and smog. MARPOL Annex VI partially regulates these emissions and recommends that tanks be equipped with vapor recovery systems (IMO MARPOL, 2009).

4.5 Metal particles

Engine wear, oil additives, and trace metals (e.g., vanadium, nickel) in fuel release metal particles into the atmosphere and marine environments. These particles can be transported long distances and accumulate in marine and terrestrial ecosystems, causing toxic effects (Saraji-Bozorgzad et al., 2025). There are currently no international limits or monitoring standards for these emissions.

4.6 Measurement challenges and regulatory gaps

A large portion of non-regulated emissions consists of compounds that are difficult to measure and model. These challenges stem primarily from:

1. Low and variable concentrations
2. Lack of standardized measurement protocols
3. The constantly changing nature of ship operations
4. High implementation costs

This delays regulatory efforts and leaves databases inadequate. The IMO, ICCT, and several research institutions are conducting reference measurement campaigns and laboratory verification studies. However, the current state of knowledge about non-regulated emissions is not yet sufficient for comprehensive regulation.

5. Future Perspectives and Policy Orientation

5.1 Forward-looking assessment: Non-regulated emissions and the need for regulation

In the context of global carbon neutrality targets (IMO 2050, EU Fit for 55), the management of not only CO_2 but also all greenhouse gas compounds are on the agenda. In this context, steps such as:

- Inclusion of BC in MARPOL Annex VI,
- Establishment of new emission factors for methane and N_2O,
- Establishing of ammonia slip limits,
- Mandatory use of tank gas recirculation systems for VOC control

are possible in the medium term (IMO MEPC, 2025).

Monitoring and controlling non-regulated emissions would not only provide environmental benefits but also provide scientific transparency in assessing the true climate impacts of fuel transition strategies.

As a result, non-regulated emissions are considered the "invisible carbon footprint" of maritime shipping. While compounds such as black carbon, methane, N_2O, and NH_3 remain outside the current regulatory systems, their impacts are comparable to regulated emissions. The vision of sustainable maritime shipping in the future depends not only on fuel conversion but also on comprehensively managing these new emissions. Therefore, a scientific, technical, and political mobilization is necessary to measure, report, and limit non-regulated emissions.

6. Conclusion and Recommendations

Maritime transport, which plays a critical role in sustaining the global economy, is increasingly under scrutiny for its environmental impact. Ship emissions are not only a byproduct of maritime operations but also a major contributor to climate change, air quality, and human health. Therefore, the sector must simultaneously balance the goals of economic sustainability and environmental responsibility.

The regulated emissions (SO_X, NO_X, CO_2, and PM) are monitored and controlled within the limits set by international and national regulations. In contrast, non-regulated emissions (CH_4, BC, N_2O, VOC, NH_3, and metal particles), although not yet comprehensively regulated, pose new threats due to their high environmental risks. This distinction provides guidance in determining the focus of future environmental strategies and policies.

In the context of international legislation, MARPOL Annex VI provides a fundamental framework for regulating ship emissions globally. In addition, regional regulations such as the European Union's ETS, FuelEU Maritime, and MRV have led to the emergence of a multi-layered management model in the maritime sector. These developments demonstrate that emissions management is no longer a mere technical engineering issue but rather an interdisciplinary field where international law, environmental policy, and trade strategy intersect.

Controlling ship emissions cannot be achieved solely through existing legislation. The growing impact of unregulated emissions also raises the environmental risks of new technologies. For example, the effects of new compounds formed during the use of green methanol, ammonia, and LNG are not yet fully understood. Therefore, future environmental policies and regulations should not be limited to carbon reduction targets; they should also incorporate fuel life cycle analysis (LCA) and environmental integrity principles.

As a result, emission management in the maritime sector is no longer merely a reactive policy but also a proactive transformation strategy. Improvements in regulated emissions must be complemented by the control of unregulated pollutants. Legislation must be supported by technological innovation, and financing mechanisms must be structured within a fair framework that prioritizes environmental integrity.

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CHAPTER 2

ADVANCED POWER SYSTEMS TO IMPROVE ENERGY EFFICIENCY IN MODERN MARINE VESSELS IN OPERATION: A REVIEW

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Abstract

Today, shipping has a significant place for transport of goods in the world. It is the most economical type of transport due to its high storage and transfer capacity. As the globalization increases, more goods are transferred through the ships and thus, the demand for low cost shipping rises in the world. A significant portion of marine transportation cost is due to fuel and energy consumption of main and auxiliary engines, which raises the issue of energy efficiency in ships. Thus, this work has the objective to review recent innovative advanced power systems for the improvement of energy efficiency in ships. Wind-assisted propulsion is one these advanced techniques to achieve enhanced energy efficiency in ships. Another option for increased energy efficiency is to use solar energy through photovoltaic panels onboard. Replacing current marine diesel oil and marine gas oil with alternative fuels such as hydrogen and liquefied natural gas (LNG) can also be highly helpful to reduce total energy requirement in marine vessels. Decreasing the waste via advanced waste heat recovery (WHR) equipment at the downstream of marine diesel engine system can increase power output and improve efficiency as well. Moreover, advanced engine technologies such as common rail high pressure injection, dual-fuel combustion and variable valve timing (VVT) can enable low fuel consumption and high-efficient main engines in current marine vessels. This chapter examines the benefits and challenges of using the above-mentioned innovative technologies for high energy efficiency in ships.

Keywords: Energy efficiency, wind energy, solar energy, waste heat recovery, marine diesel engines, alternative fuels.

1. Introduction

Currently, marine transport is considerable for the continental transfer of oil, coal, several minerals and chemicals, agricultural products, foods, machinery and various kinds of highway vehicles. Tankers and containerships, in particular, play a noticeable role for the sustainability of worldwide trade. The reason marine transport is more preferred compared to rail and highway transport, particularly between long distances, is that it is more cost effective, which is desirable for the shipowners [Protopapas et al. (2013)]. The possibility of storing and transferring large amounts of goods through large marine vessels decreases the unit shipping cost and thus, close to 90% of total transport is achieved through ships in the globe [Singh et al. (2023)]. It is seen that this trend is likely to continue as increasingly larger commercial ships are built to improve the storage capacity of marine vessels.

Nowadays, the propulsion of modern commercial ships mostly depends on marine diesel engines (MDEs). In general, two-stroke low-speed MDEs are preferred to drive large vessels such as tankers and four-stroke high-speed MDEs are utilized to propel small vessels such as tugboats. MDEs are reliable, durable and cost-effective due to high thermal efficiency. However, they still need the consumption of high rates of marine diesel oil (MDO), marine gas oil (MGO) or heavy fuel oil (HFO) during operation. The combustion of those carbon-based fuels leads to the release of a significant amount of carbon monoxide (CO), carbon dioxide (CO_2) and nitrogen oxide (NOx) to the surrounding, which not only increases the global warming but is also detrimental to human health [Aakko-Saksa et al. (2023)]. Due to sulphur content in the fuel, marine vessels emit high rates of sulphur oxide (SOx) as well, which is harmful to marine life and need to be reduced to desirable levels to protect the ocean environment [Tadros et al. (2023)].

In order to improve aforementioned emission rates due to marine vessels within a plan, International Maritime Organization (IMO) demands that greenhouse gas (GHG) emissions from ships be reduced by 50 percent by 2050 compared to 2008. Also, to accelerate the decarbonization of ships, IMO aims to diminish the CO_2 rates due to ships in 2030 by 40% and in 2050 by 70% [Bilgili & Ölçer (2024); Joung et al. (2020)]. These aims are highly stringent and technically challenging for the shipowners and some practical measures need to be developed to limit GHG rates in ships [Sarbanha et al. (2023)]. Considering the current high emission rates are directly linked to the total energy expenditure of the marine vessels, improved energy efficiency is necessary to satisfactorily reduce the GHG rates due to ships [Jimenez et al. (2022)]. Moreover, more industrial products will probably need to be transferred via ships due to cost-effectiveness and it will be more difficult to provide carbon-based fuel for ships as reserves dwindle in the near future. Thus, energy-efficient ships will be needed to meet the rising global demand in maritime transport [Ang et al. (2017)].

As a marine vessel increases in size or is loaded at a higher rate, the energy consumption required for steady operation during its route and thus, emissions to the environment rise significantly, which is undesirable. The control of energy consumption appears to be a key element to limit engine-out emission rates to desirable levels in a marine vessel. Therefore, this work concentrates on a comprehensive review of emerging innovative advanced power systems for the improvement of energy efficiency in ships. Wind-assisted propulsion, utilization of solar power, alternative fuels, waste heat recovery systems and advanced fuel-efficient engine technologies are examined as emerging innovative methods to achieve high energy efficiency in marine vessels. The challenges that these technologies have to overcome before their practical application in ships are also presented in the following sections.

2. Energy Efficiency of Ships

Maritime transport, constituting a major share in the total transport of goods in the world, currently depends on fossil fuel consumption in marine vehicles. However, the fuel prices are unstable and the emission rates due to ships are a significant concern for environmental agencies. Therefore, the requirement for low fuel consumption and stringent emission limits force marine engineers to search novel techniques to enhance energy efficiency in ships operation.

2.1. Energy efficiency design index (EEDI)

Maritime transport is cost-effective compared to highway, rail and air transport since more amount of goods can be carried through ships and thus, cost per unit transported and energy consumed is reduced. However, it is realized that more can be achieved by the maritime industy to enhance energy efficiency in ships. In this regard, IMO has issued some standards for higher efficiency in marine vessels. One of those standards is the Energy Efficiency Design Index (EEDI) [IMO (2011)]. The EEDI aims to provide a particular figure for the CO_2 emissions of a specific ship for a given speed and design cargo loading condition considering the required fuel consumption due to propulsion and other auxiliary machinery. It is expressed with grams of CO_2 per vessel's capacity-mile and is calculated through a complex technical formula, which uses the design parameters of an individual ship. EEDI demands a minimum energy efficiency level for the vessel considering its type and size. The lower the EEDI is kept, the higher energy efficient the ship is maintained and the better the ship is designed for new regulations [Vasilev et al. (2025)].

2.2. Ship energy efficiency management plan (SEEMP)

One other significant standard is the Ship Energy Efficiency Management Plan (SEEMP). It is considered as a very helpful tool for shipowners to improve both efficiency and environmental effects of ships [DNV (2025a)]. SEEMP mainly includes 3 parts. Part 1 is related to the management strategy for enhanced energy efficiency in ships. Part 2 considers the plan for keeping and storing the consumption rate of fuel oil for the ship. Finally, part 3 concerns the carbon intensity plan for vessel operations. Part 1 is essential for all marine vessels above 400 GT and the efficiency management plan should be held on board. Part 2 is essential for all marine vessels exceeding 5000 GT. The collection of fuel consumption data is significant for those ships. Part 3 is mandatory for ships, which are contingent on Carbon Intensity Indicator (CII), such as cruise passenger and cargo vessels larger than 5000 GT. Overall, SEEMP leads shipowners to apply new strategies such as optimizing vessel speed and vessel route, supporting the propulsion with renewable energy or fitting the ships with heat recovery units and devise new management plans to reduce the fuel/energy consumption of ships [Dewan and Godina (2023)]. The fundamental elements of SEEMP, from weather routing to hull monitoring and optimized cargo handling, are demonstrated in Figure 1 [Issa et al. (2022)].

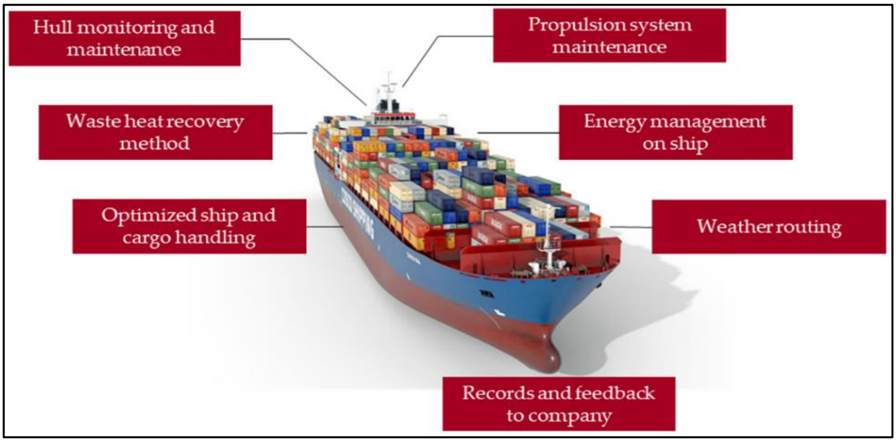

Figure 1. The main elements of SEEMP [Issa et al. (2022)].

3. Advanced Power Systems for Improved Energy Efficiency

Ships are built in various sizes and for different purposes. Total energy demand is mostly defined by the ship type, which considers the particular energy requirement for the ship. While small cruise vessels transport hundreds of passengers at high speeds over short distances, containerships transport hundreds of containers at relatively low speeds over long distances. Considering the route, the speed and the trim of the ship, the total energy consumption for main and auxiliary machinery systems vary significantly depending on the ship type [Fan et al. (2022)]. Therefore, the need in energy improvement can change from a small vessel such as a tugboat, to a large vessel such as an oil tanker [Ma et al. (2025)]. The following methods can be a solution for almost all types of ships. However, the effectiveness of the techniques and additional costs should be considered depending on the vessel type. The potential of solar energy for efficiency improvement is examined first in the following subsection.

3.1. Ship propulsion via solar energy

Solar energy can be regarded as a noticeable innovative technique for the improvement of energy efficiency in ships. Not only is it sustainable, but it is also considered clean, as assisting ship propulsion with solar power can reduce emission rates significantly [Wu et al. (2024)]. Mainly, in solar-powered boats, solar panels are utilized onboard to maintain the electrical power for different machinery units on the vessels. The working mechanism of solar panels on a boat is illustrated in Figure 2 [Pure Power Solutions (2025)]. The electrical power produced through photovoltaic panels is stored in marine batteries and then used to drive refrigeration, electronics and other auxiliaries such as lights or navigation. If the battery is powerful, solar power can be utilized to assist the propulsion of the vessel as well [Minak (2023)]. A charge controller is also placed in a solar-assisted boat, as in Figure 2, to modulate the battery charging and prevent a possible overcharging, which can lead to undesirable heat rise or an operation failure in the system.

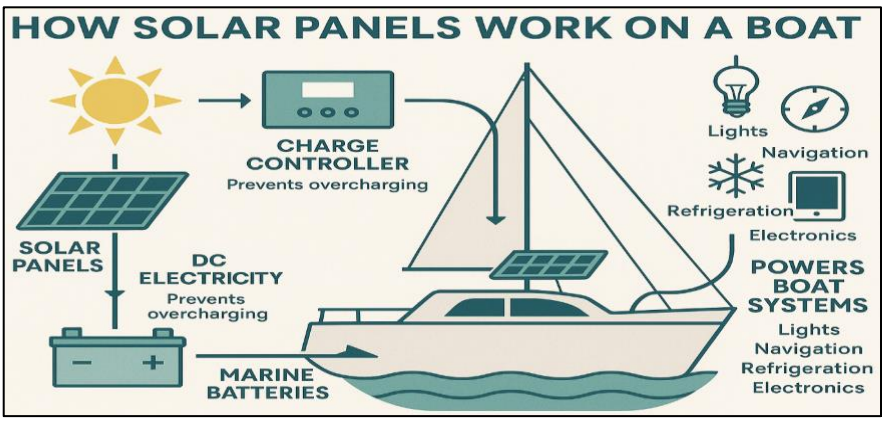

Figure 2. Solar power operation mechanism on a boat [Pure Power Solutions (2025)].

The high power requirement of large vessels and limited area onboard mostly force researchers to apply solar power in relatively small vessels such as small passenger boats or fishing boats [Setiyobudi et al. (2023)]. However, large-scale solar power is explored in hybrid power systems, as combination with diesel generator power, as well [Yuan et al. (2018)]. Nyanya et al. examine the optimization of wind and solar energy capture for the propulsion system of a bulk carrier through two different models [Nyanya et al. (2021)]. While one model focuses on the sail angle for different wind conditions, the other model concentrates on the optimization of the total deck area for wind and solar units. It is seen that, in comparison to non-renewable ship operation, optimizing the sail angle and the usable deck space for solar and wind equipment onboard maximizes the power produced through renewables and results in a 36 %

decrease in CO_2 emission rates. Zhu et al. quantify the impact of use of solar power as auxiliary power on the EEDI of new building ships [Zhu et al. (2017)]. The work particularly focuses on the effect of different declination angles and latitudes for solar energy availability for ships. It is stated that the solar radiation obtained on the solar panels can be maximized by optimizing the declination angle. The available maximum solar energy can then be utilized on the new building ships to decrease CO_2 rates and meet the strict IMO regulations. Koenhardono et al. study the effect of solar-assisted hybrid power system on the energy efficiency of a tanker [Koenhardono et al. (2022)]. A fuel consumption improvement of 15.5 % per year can be yielded via placing solar panels on the deck and providing power for the electrical equipment on the ship.

As the requirements for energy efficiency and emission regulations get more stringent, solar photovoltaic (PV) panels are predicted to be used more commonly in ships [Kasaeian et al. (2025)]. A solar PV system is theoretically developed by Karatuğ and Durmuşoğlu for a Ro-Ro vessel, which navigates between Pendik and Trieste [Karatuğ and Durmuşoğlu (2020)]. It is stated that energy efficiency is improved by 7.76 % and the designed solar unit can satisfy 7.38 % of the Ro-Ro ship's fuel need. The advantages of solar PV panel use in ships are summarized in Figure 3 [Abdullah-Al-Mahbub et al. (2023)].

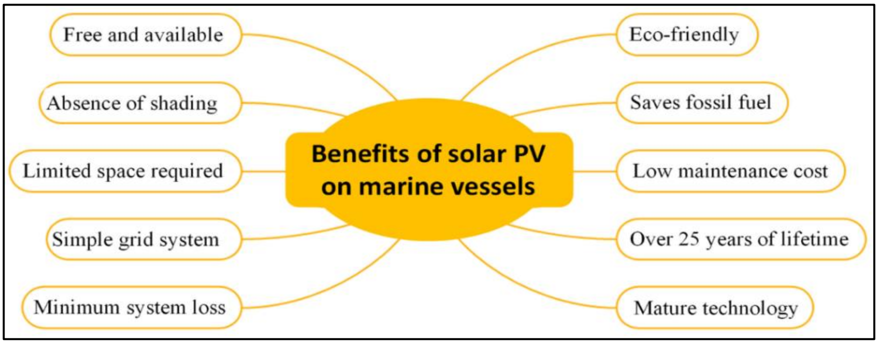

Figure 3. Advantages of using solar photovoltaic panels on marine vessels [Abdullah-Al-Mahbub et al. (2023)].

3.2. Ship propulsion via wind energy

In addition to solar energy, wind energy also has a noticeable potential to improve energy efficiency in ships. Wind energy is clean and renewable and thus, can be a significant support to improve decarbonization in ships. In general, three leading technologies are applied to produce useful propulsion power in marine vessels, namely kite sails, wing sails and Flettner rotor [Chou et al. (2021)]. The major wind power technologies are demonstrated in Figure 4 [Chapman (2010)]. Soft sail and wind turbines can also be utilized to harness wind energy on ships. Kite sails (or Kite Rig) depends on the position of the kite (height from the deck) and can be dynamically controlled. Flettner Rotor is based on the magnus effect, which creates the ship propulsion force through the rotating rotors placed on the deck [Nuttall and Kaitu'u (2016)]. Wing sails are controllable airfoil structures located above the deck to generate additional driving force for the ship [Milić Kralj and Klarin (2016)].

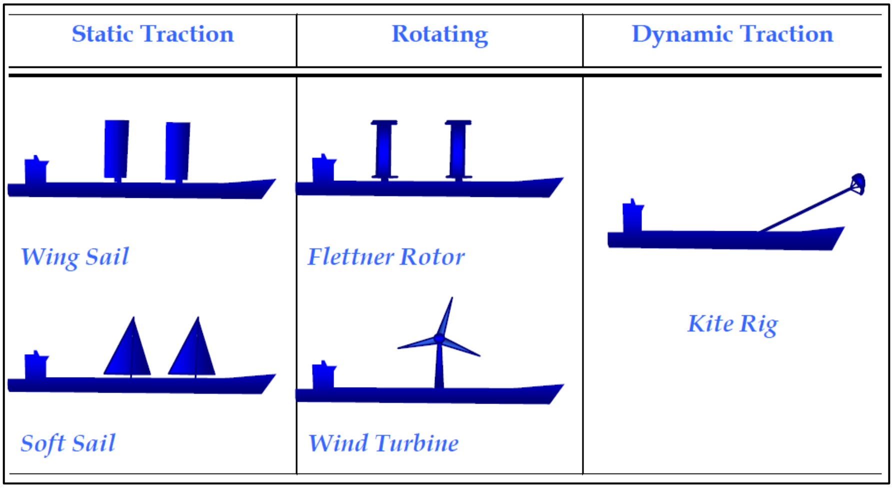

Figure 4. The main wind power technologies in ships [Chapman (2010)].

Seddiek and Ammar explore the potential of Flettner rotors to support propulsion power on a bulk carrier [Seddiek and Ammar (2021)]. It is stated that the useful power due to rotors is noticeably affected by wind speed, wind direction and also ship course. In the case study, each rotor generates on average a power output of 384 kW/h. Up to 22 % of the bulk carrier's annual fuel consumption can be met through the power produced by rotors and NOx and CO_2 rates can be decreased 270.4 ton/year and 9272 ton/year, respectively. A set of successful wind tunnel tests are achieved by Bordogna et al. to quantify the effect of Reynolds number on the effectiveness of Flettner rotors [Bordogna et al. (2019)]. It is seen that at different velocity ratios, the drag and lift coefficients can vary for different Reynolds numbers, which affects the performance of Flettner rotors. Moreover, a numerical model is developed by Vigna and Figari to assess the potential of Flettner rotor for auxiliary propulsion power support on a ship [Vigna and Figari (2023)]. As a case study, the model is applied for a Ro-Ro/Pax ferry navigating in the Mediterranean Sea. It is seen that fuel consumption can be improved over a range of 4 % to 6 % and the power need of the ship can be enhanced due to use of Flettner rotors over a range of 5 % and 10 % for a moderate wind condition in the Mediterranean. Similar works examining the Flettner rotors on ships also demonstrate the fuel-saving and environmentally positive effect of this technology [Angelini et al. (2023); Li et al. (2024a)].

Not only using Flettner rotor, but also kite sails is beneficial to harness wind energy and decrease the fossil fuel-based energy consumption in ships [Fritz (2013)]. Formosa et al. numerically analyze the effect of kite area and wind speed on the propulsive support of the kite sail system in a 75 m – long Series 60 ship [Formosa et al. (2023)]. It is claimed that the total propulsion power need of a ship can be successfully satisfied via a kite sail area of 320 m^2 within proper wind conditions. Traut et al. compared the Flettner rotor and kite sails for different shipping routes through using a numerical model [Traut et al. (2014)]. For the routes chosen, it is seen that kite sail has the potential to generate an average power output in a range of 127 kW to 461 kW in the analysis. Kite sail is found to be not as consistent as Flettner rotors. However, it has the capacity to produce higher power output and requires relatively lower area on the deck than Flettner rotors and thus, can be more economical to sustain reduced-carbon shipping. Other than kite sails, Ouchi et al. utilize hard wing sails to provide ship propulsion power [Ouchi et al. (2011)]. In a CFD model, 9 sets of composite wings are located on the deck of a 180,000 DW bulk carrier and the thrust of the ship is examined for different wind scenarios. It is seen that more than half of the propulsion power of the ship can be met via the wing sail-harnessed wind energy when the bulk carrier is assumed to operate in the Pacific trade wind area of Hawai islands. In a similar CFD-dependent work, Hussain and Amin explore the impact of different drifting angles on the effectiveness of hard wing sails for the propulsion assistance for a bulk carrier [Hussain and Amin (2021)]. It is concluded that up to 37.6 % decrease in ship propulsion power is possible within favourable wind conditions. Overall, these aforementioned works are highly valuable for the widespread use of wind energy and the improvement of fuel consumption in ships. However, the transition from the conventional diesel engine-based propulsion to those hybrid power systems is predicted to be slow since the energy saving and the payback period for the installation cost of these technologies is still not certain and further work is needed to overcome those challenges [Rehmatulla et al. (2017)].

3.3. Alternative fuels

Replacing current marine diesel fuel with alternative fuels can be effective to improve both energy efficiency and undesirable GHG emissions in marine vessels. Different fuels, alone or in combination with marine diesel fuel, are directly tested by researchers to improve emission rates due to ships. In general, ammonia, methanol, hydrogen and liquefied natural gas (LNG) can be highly beneficial to enhance fuel efficiency in ships [Hellström et al. (2024)]. As in Figure 5, there is a consistent rise in alternative fuel demand for ships since 2015 [DNV (2025b)]. This trend is expected to continue in 2025 and beyond.

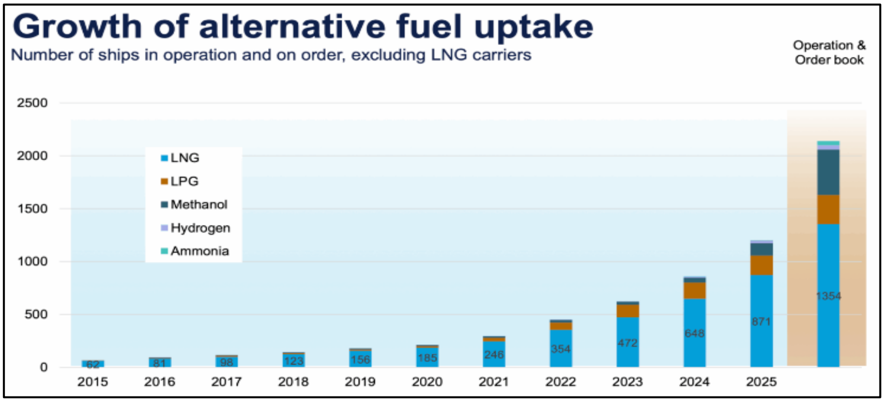

Figure 5. The rise of alternative fuel usage in ships [DNV (2025b)].

One option is to supply methanol to produce propulsion power in ships [Nunes (2025)]. Ammar examine the environmental and economic impact of methanol usage for a containership [Ammar (2019)]. It is shown that utilizing a dual-fuel engine (MDO of 11 % and methanol of 89 %) can decrease NOx and CO rates by 76.78 % and 55 %, respectively. It is also stated that the ship speed should be lowered by 28 % in order to decrease the dual-fuel cost. Methanol includes no sulphur content, which is helpful to satisfy the strict SO_x legislations of IMO for ships. Moreover, Karvounis et al. demonstrate in a CFD model-based work that, compared diesel alone operation, indicated thermal efficiency of a diesel-methanol dual fuel marine engine can be improved by 4.2 % via direct methanol injection [Karvounis et al. (2025)]. It should be considered that dual-fuel engines mostly necessitate double fuel pumps and double fuel injectors, which can be technically challenging for next-generation ship engines. However, in the long term, the benefits of methanol in Nox and Sox rates can be more economical for the shipowners compared to using conventional exhaust after-treatment systems such as SCR or marine scrubbers [Wu et al. (2025)].

Another effective alternative fuel can be ammonia for ships. Inal et al. compare the decarbonization potential of hydrogen and ammonia for shipping operations in terms of different criterias [Inal et al. (2022)]. It is found that ammonia performs marginally better than hydrogen as an alternative fuel considering emissions, storage, safety and cost. Song et al. explore the effect of natural gas, ammonia, methanol and hydrogen on the energy efficiency of maritime supply chain [Song et al. (2022)]. It is shown that, among all aforementioned alternative fuels, methanol is the most fuel saving, ammonia is found to be the second fuel efficient, which has the potential to obtain an energy efficiency of 97.37 % for cargo handling system. In addition to ammonia, liquid hydrogen can be considered as a feasible fuel for marine vessels. As hydrogen does not cause any significant CO_2 rates, it is highly suitable for strict decarbonization plan of IMO for 2050 [Li et al. (2024b)]. Aarskog et al. analyze the economic feasibility of a hydrogen-powered high speed passenger ferry navigating in Norway [Aarskog et al. (2020)]. It is demonstrated that currently, the propulsion of the passenger ferry through hydrogen costs 28 % higher than diesel fuel. However, as the fuel cell system cost and fuel cost of hydrogen are projected to decrease towards the end of the 2020s, hydrogen-based propulsion can be realized between 2025 and 2030 with a similar cost of diesel-based propulsion but without any CO_2 emissions. Despite the possible practical application of hydrogen in small vessels in the coming future, the high cost of cryogenic storage tanks for liquid hydrogen can be challenging for the implementation of hydrogen-powered propulsion in relatively high-tonnage marine vessels [Zhang et al. (2023)]. The low progress in hydrogen infrastructure can also be a problem for large commercial ships.

There are significant works for considering methanol, ammonia and hydrogen as a possible energy source for ships. However, in the short term, 11ulphur11d natural gas (LNG) is seen to be the most practical option for ships in operation [Burel et al. (2013)]. Altosole et al. observe that, compared to conventional diesel oil, using LNG enables an improved exploitation of engine-out exhaust energy and thus, leads to a greater availability of steam and a higher generation of additional electric energy for the ship [Altosole et al. (2018)]. Despite the role of enhanced energy efficiency for ship propulsion, it is noted that LNG consists primarily of methane (CH_4) and is a carbon-based alternative fuel. Thus, its capacity to improve CO and CO_2 emission rates can be relatively limited in comparison to hydrogen and ammonia. However, LNG involves no 11ulphur content and does not cause any Sox and can reduce Nox rates significantly in comparison to current marine fuel oils [Anderson et al. (2015)]. Also, considering the experience gained in LNG carriers, the bunkering system of LNG is more advanced and technological maturity of LNG combustion is more improved compared to other alternative fuels. Those advantages are certainly helpful to consider LNG as a feasible replacement for HFO and MDO.

3.4. Waste heat recovery (WHR)

A significant amount of heat is necessarily rejected into the surrounding as exhaust gas energy in diesel engine systems due to the 2^{nd} law of thermodynamics. As shown in Figure 6, a noticeable amount of fuel energy is lost for radiation, lubrication oil, jacket water, air cooler and exhaust gas and cannot be converted to useful shaft power in ships [Zhu et al. (2020)].

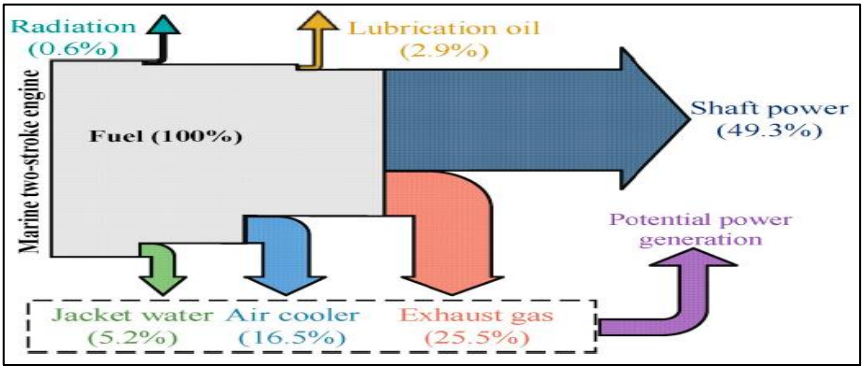

Figure 6. Energy balance for a 2-stroke marine engine [Zhu et al. (2020)].

Producing useful work via directing the exhaust gas into proper additional equipment is a solution to lower the amount of wasted energy and improve energy efficiency in ships. This is generally achieved with WHR systems in ships [Singh and Pedersen (2016)]. Generating electrical power from the recovered heat can meet partially the power need of the electrical and heating units of the vessel (reduced auxiliary machinery power demand) or can be an effective support for propulsion, as in Figure 7 [Miller et al. (2024)]. Thus, total useful power from a similar amount of fuel consumption is increased in ships.

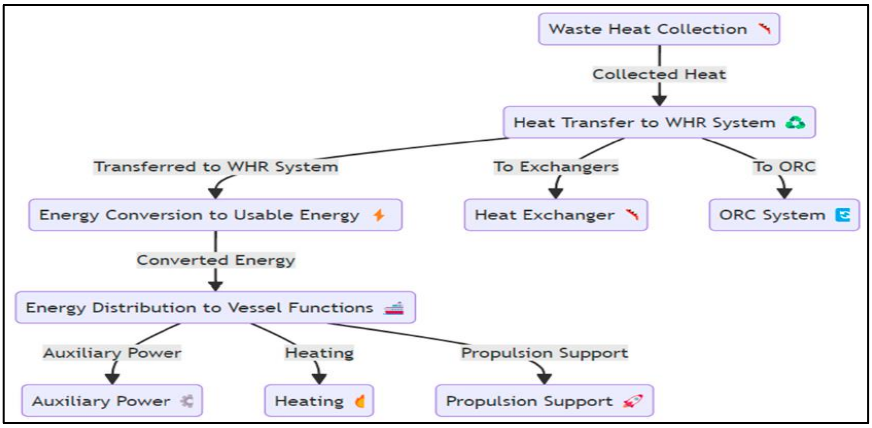

Figure 7. Evaluation of WHR for different purposes on a ship [Miller et al. (2024)].

Baldi and Gabrielii investigate the practicality of WHR for ship operations [Baldi and Gabrielii (2015)]. A relatively simplified model is proposed to assess the energy and exergy availability of WHR unit for a marine vessel. As a case study, the model is applied for a chemical tanker and it is claimed that a range of 5 % to 15 % fuel saving can be obtained via recovering the wasted heat in the system. Grljušić et al. examine the fuel consumption improvement for WHR combined heat power plant for an oil tanker utilizing organic fluids [Grljušić et al. (2015)]. It is observed that as the ship's main engine performs at 65 % or higher of its MCR, greater than 5 % improvement can be achieved for the power plant thermal efficiency. Ma et al. analyze the effect of different WHR systems, through combined turbines, Rankine cycle and Organic Rankine Cycle, on the energy efficiency for a 10000 TEU conceptual container ship powered by a 2-stroke diesel engine [Ma et al. (2017)]. The study concludes that the container ship can meet IMO's 2nd stage EEDI requirements by reducing the EEDI up to 23.08 % with the installation of a proper WHR system.

Effective heat exchangers are significant, particularly for Rankine cycle-based WHR systems, to enhance the total recovered waste heat and thus, to produce more useful power in ships. In the future, with nanotechnology-based works, the surface area can be improved for heat exchangers and thus, the efficiency of the WHR can be further increased [Ononogba et al. (2023)]. Moreover, thermoelectric generators can be more preferred in WHR systems of ships due to low noise, high reliability, performing environmentally positive and without working fluids and the ability to convert thermal energy directly into electrical energy. Therefore, advanced thermoelectric generators can be effective to achieve more environmentally friendly and more efficient WHR systems in ships [Burnete et al. (2022); Fisher et al. (2024)].

3.5. Advanced marine engine technology

Modern diesel engine technology has advanced considerably since its invention at the end of the 19th century. Diesel engines now consume much less fuel, emit much less pollutants and perform much more reliable. However, it is realized that there is still room for the improvement of this technology and engine producers are in an ongoing research to develop more efficient, more reliable and more environmentally friendly diesel engines [Dahham et al. (2022)]. This continued effort helps reduce the fuel cost and delays a possible shift to other propulsion technology in ships. Thus, marine diesel engines are seen as key propulsion unit in marine vessels until battery-based electrical propulsion matures and performs reliably in ships [Curran et al. (2024)].

Currently, common rail direct injection (CRDI) is applied in diesel engine systems to maintain effective combustion. CRDI is advantageous since it only needs one pump to inject fuel into multiple cylinders, causes low noise, low smoke and PM rates, modulate the fuel flow considering the engine load and engine speed and performs fuel economical. Increasing the injection pressure in those systems improves the in-cylinder combustion process and enables further improvement in fuel efficiency [Liu et al. (2019)]. Therefore, advanced and reliable high pressure CRDI systems can be a solution to achieve high energy efficiency in marine vessels [Hu et al. (2020)].

In addition to CR fuel injection, variable valve timing (VVT) is developed as a highly promising technique to increase diesel engine efficiency [Basaran and Ozsoysal (2017)]. Unlike conventional systems, VVT can regulate in-cylinder flow via flexible valve timings, reducing engine loss. Wang et al. design an experimental setup to test the impact of Miller cycle, as late intake valve closure, in a 2-stage turbocharged marine diesel engine [Wang et al. (2021)]. The fuel efficiency is improved by 2.88 % and the NOx rate is enhanced by 17.36 % at 25 % propulsion load via Miller timing. Other than engine systems using diesel fuel, Lai et al. experimentally analyze the effect of VVT for a direct-injection hydrogen engine [Lai et al. (2025)]. The study states that optimized VVT has the potential to improve brake thermal efficiency up to 42.57 %. Not only is VVT helpful to improve engine fuel consumption through effective gas exchange process, but also it is useful for controlling exhaust temperature and therefore SCR efficiency and minimizing NOx rates [Soleimani et al. (2025); Basaran (2023)]. Due to the energy efficiency and emission improvement advantages mentioned above, the demand for VVT systems in marine engines market is predicted to rise from 203.7 units in 2024 to 563.2 units in 2030, as illustrated in Figure 8 [Research and Markets (2025)].

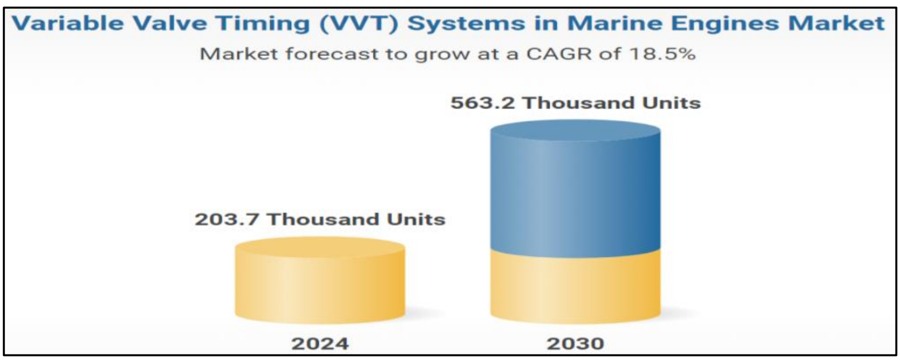

Figure 8. The predicted increase of VVT systems in marine engines market [Research and Markets (2025)].

Developing more effective combustion techniques, advanced VVT methods [Başaran (2021)], introducing dual-fuel combustion, improved engine insulation, enhanced pumping and friction loss and effective WHR systems are highly significant to achieve a brake thermal efficiency of 50 % for heavy-duty diesel engines [Delgado and Lutsey (2014)]. Moreover, SCR and marine scrubbers noticeably reduce the undesirable NOx and SOx rates. However, the conventional diesel engine based power systems are completely dependent on HFO, MDO and MGO, and they still cause environmental pollution. It is challenging for the shipowners to meet the strict emission regulations of IMO via using marine diesel engines alone in ships. There is a need to reduce the role of conventional fuels in ship propulsion. Therefore, there is a shift towards to hybrid forms of power systems, as demonstrated in Figure 9, to diversify the energy supply to the ship and reduce NOx and CO rates [Yuan et al. (2020)].

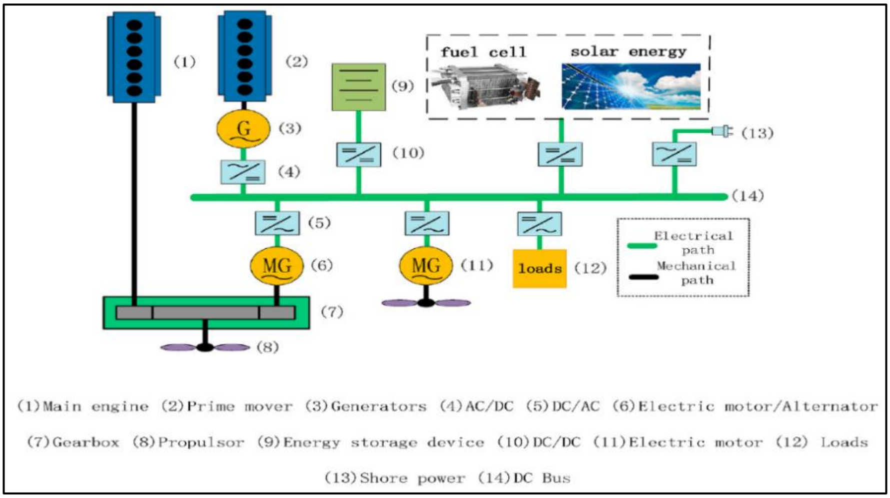

Figure 9. The schematic of a typical parallel hybrid power system for a ship [Yuan et al. (2020)].

In those hybrid systems, there is still a main engine (a marine diesel engine or a marine gas turbine) for the propulsion. However, in addition to mechanical path, there is also an electrical path in which electric motors can be activated by secondary diesel engines or solar energy and fuel cell systems or other energy storage devices. The mechanical and electric paths can operate independently or in a combined manner whenever needed in the vessel. Any excessive power of the main engine can be channeled to an electric motor, which can work in generator mode and supply the additional power to the grid for future use on board. Hybridized solid oxide fuel cells (SOFC) and marine diesel engine or gas turbine systems is one of the emerging innovative techniques to improve both engine performance and emission rates in ships [Park and Choi (2025); Li et al. (2024c)]. It is considered that those advanced hybrid power units, CRDI and VVT [Başaran (2024)] can be attractive for commercial ships until battery technology is adequately developed to drive high gross-tonnage vessels and the infrastructure for battery charging systems in ports is sufficiently organized.

4. Conclusions

This work aims to review the current effective innovative techniques to improve energy efficiency in marine vessels in operation. Considering the stringent goals of IMO for decarbonization of ships, at least some auxiliary power supply, as an assistant unit to the marine diesel engine, should be placed not only to curb criteria pollutants in ships but also improve fuel economy for maritime operations.

Solar power in ships is seen to be effective to decrease total fuel consumption and improve CO and CO_2 rates. However, at present, PV panels are still inadequate to supply the total required propulsion power for particularly large vessels. Therefore, it is seen that solar power will assist ship propulsion or supply the energy for auxiliary machinery for the near future, rather than being the main driving force. Another clean and renewable energy source, wind power, can be practically applied in ships via wing sails, kite sails or Flettner rotors. Those wind-based technologies directly contribute the propulsion through generating additional lift force for the ship and thus, enhance energy efficiency in ships. High installation cost and uncertainties on harnessed wind power during vessel route are the challenges that need to be solved for reliable future wind-assisted applications. Alternative fuels such as hydrogen and ammonia can be utilized in combined with MDO or HFO to minimize carbonization in ships as dual-fuel combustion technology is sufficiently developed. Despite less effective in improving decarbonization, LNG can also be a promising replacement for the conventional marine fuels as it has the most matured technology among all alternative fuels. The high cost due to liquid storage of hydrogen and LNG and the underdeveloped infrastructure for fuel bunkering in ports should be overcome before a transition to those fuels is realized in ships. Current WHR systems increase the machinery installation cost. However, recovering more amount of wasted heat via advanced ORC systems or turbocharging units can improve the payback periods and result in significant rise in energy efficiency in ships. Advanced VVT, high-pressure CR injection and hybrid propulsion systems (MDE + fuel cell, solar or battery-based electrical power) can also improve energy efficiency in current and future ships.

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CHAPTER 3

AN OVERVIEW OF THE ORGANIC RANKINE CYCLE WASTE HEAT RECOVERY SYSTEMS ONBOARD SHIPS

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Abstract

This chapter presents an overview of Organic Rankine Cycle (ORC) waste heat recovery (WHR) technology for ships, focusing on its potential to increase energy efficiency in maritime operations. Key waste heat sources, including exhaust gases, jacket cooling water, and scavenge air, are evaluated and classified based on their energy quality and recovery potential. Criteria for selecting suitable working fluids are examined with respect to thermal efficiency, environmental impact, safety, and compatibility with marine conditions. Various ORC system configurations integrated with marine engines are critically analyzed, highlighting performance, operational considerations, and challenges reported in prior studies. The chapter concludes with insights and recommendations for future research, emphasizing the role of ORC WHR systems in improving EEDI, EEXI, and CII compliance, supporting decarbonization strategies, and guiding the practical implementation of energy-efficient shipping solutions.

Keywords: Ship energy efficiency, Waste heat recovery, ORC, Alternative fuels.

1. Introduction

Maritime transport continues to serve as the driving force of global trade, with approximately 80% of goods worldwide, in terms of tonnage, carried by sea (UNCTAD, 2025). In 2023, the total volume of goods transported reached 12,292 million tons, representing an annual increase of 2.4%. Meanwhile, trade measured in ton-miles rose by 4.2% compared to the previous year, amounting to 62,037 billion ton-miles (UNCTAD, 2024). Alongside this expansion, the shipping sector is under pressure to decarbonize, driven by regulatory requirements, market incentives, stakeholder demands, and rising public expectations for sustainability. Recent data highlight that maritime transport accounts for approximately 3% of global greenhouse gas (GHG) emissions and underscore that, without mitigation measures, these emissions could exceed 2.3 times their 2008 levels by 2050 (IMO, 2021). The International Maritime Organization (IMO) has launched key measures, including the Energy Efficiency Design Index (EEDI), the Ship Energy Efficiency Management Plan (SEEMP), and the Energy Efficiency Operational Indicator (EEOI), complemented by emission regulations under MARPOL Annex VI. Furthermore, through amendments to MARPOL, the IMO has expanded the scope of energy efficiency measures, making mandatory the Existing Ship Energy Efficiency Index (EEXI), the Carbon Intensity Indicator (CII), and enhanced SEEMP practices. In this context, the IMO aims to reduce the carbon footprint of maritime transport by 20% by 2030 and by 70% by 2040 (IMO, 2023).

On the other hand, achieving the IMO's targets still entails substantial challenges, and various methods are available to reduce emissions at both the design and operational stages of ships. Measures such as hydrodynamic design optimization (Barreiro, Zaragoza, & Diaz-Casas, 2022; Bulut, 2025), exhaust gas cleaning (scrubbers), exhaust gas recirculation (EGR), selective catalytic reduction (SCR), integration of carbon capture and storage systems (Akman, 2023; Güler & Ergin, 2021), use of renewable energy (Huang, Fan, Xu, & Liu, 2022), slow steaming, and route optimization (Barreiro et al., 2022; Dere & Deniz, 2019) offer important solutions for regulatory compliance; however, in view of long-term decarbonization objectives, the transition to low- or zero-carbon fuels is considered the fastest and most effective pathway (Ampah, Yusuf, Afrane, Jin, & Liu, 2021). Consequently, the deployment on ships of multi-fuel engines capable of burning liquefied natural gas (LNG), liquefied petroleum gas (LPG), methanol (MeOH), ethanol, ammonia, or hydrogen represents one of the main strategies to reduce the environmental impacts of conventional heavy fuel oil (HFO) or marine diesel oil (MDO). Indeed, alternative fuels, in line with IMO emission limits, can lower greenhouse gas (GHG), sulfur oxide (SOx), nitrogen oxide (NOx), and particulate matter (PM) emissions to much lower levels. The most recent reports show that the use of methanol, LNG, and LPG as primary fuels can reduce SOx and PM emissions by over 90%, and CO_2 and NOx emissions by 10–50% compared with HFO Tier II (MAN, 2021). Dual-fuel engines running on gas and diesel typically meet Tier II NOx and SOx standards, whereas EGR or SCR systems are employed when compliance with the stricter Tier III limits is required. However, as with conventional two-stroke diesel engines, dual-fuel engines lose roughly half of the fuel energy through exhaust gases and cooling fluids (Akman & Ergin, 2023; MAN, 2020), which underscores the need for waste heat recovery technologies such as the Organic Rankine Cycle.

Organic Rankine Cycle waste heat recovery technology has recently gained attention as a promising solution for enhancing ship energy efficiency and cutting emissions. In two-stroke marine engines, approximately 25% of the total fuel energy is lost through exhaust gases, 16% through scavenging air, 5% through jacket cooling water, and 3% through lubricating oil, which are all low-quality waste heat sources (Singh & Pedersen, 2016). Moreover, considering the stringent and up-to-date regulations aimed at reducing the carbon footprint of ships, ORC WHR systems are deemed capable of making significant contributions to compliance with measures such as the EEDI, EEXI, and CII (Akman & Ergin, 2022; Lyu, Kan, Chen, Zhang, & Fu, 2023). Accordingly, numerous studies have been conducted on the application of ORC WHR systems in ships. Recent research focuses on the optimization of thermodynamic and thermo-economic performance of ORC or hybrid ORC systems, along with environmental impact assessments. On the other hand, owing to its higher-quality waste heat content compared to jacket water and scavenging air, exhaust gas stands out as the primary waste heat source for ORC systems in practical applications (Singh & Pedersen, 2016; Yang, 2016). Altosole et al. (2023) reported that in a power generation system operating on liquefied natural gas (LNG) and marine diesel oil (MDO), the efficiency of an ORC-integrated power generation system can increase by approximately 2% when the main engine operates in the natural gas mode. Chen et al. (2023) analyzed simple and regenerative ORC systems for the recovery of exhaust gas and jacket cooling water in an HFO-fueled system, reporting a fuel saving of 510 tons and a reduction of 1,581 tons of carbon emissions with the regenerative ORC configuration. Reale et al. (2023) integrated an ORC cycle with a preheated and regenerative supercritical CO_2 Brayton cycle in an LNG-fueled system, using R1336mzz(Z) as the working fluid, and reported an exergy efficiency of over 45%. Xu et al. (2024) evaluated the performance of an ORC system integrated with a thermoelectric generator (TEG) in a hybrid MDO-powered propulsion system, achieving a maximum energy saving of 13.47%. Similarly, Elkafas (2024) indicated that an ORC-TEG system integrated with the main engine of a container ship could generate 1,386 kW of power and yield an annual fuel saving of 1,580 tons. Gao et al. (2025) developed a dual-loop ORC-carbon capture system utilizing LNG flow, achieving a net power output of 305 kW and a carbon capture rate of 90.56% under optimized conditions, with R290 and R601 as working fluids. Li et al. (2025) developed a methanol-based hybrid system, reporting an electrical efficiency of 58.37% through the integration of a solid oxide fuel cell (SOFC), main engine, and ORC, using R113, R141b, and R245fa as working fluids. Besides, authors of the study, Akman et al. (2025), investigated the performance of an Organic Rankine Cycle (ORC)-based waste heat recovery system utilizing the jacket cooling water of a methanol-fueled dual-fuel marine engine under different operational loads. They reported that using working fluids with very low global warming potential (GWP) could enhance the thermal efficiency of the power generation system by more than 1%, potentially preventing approximately 5000 kg of CO_2 emissions annually.

Motivated by this background, this chapter provides a comprehensive review of Organic Rankine Cycle (ORC) waste heat recovery (WHR) technology onboard ships, highlighting its potential for improving energy efficiency and reducing emissions in maritime operations. The chapter begins with an evaluation and classification of the main waste heat sources onboard, including exhaust gases, jacket cooling water, and scavenge air, emphasizing their energy quality and potential for recovery. Next, the criteria for selecting suitable working fluids for marine ORC applications are discussed, considering thermal efficiency, environmental impact, safety, and compatibility with marine conditions. Following this, various ORC WHR systems integrated with marine engines are introduced, with a critical analysis of configurations, system performance, and operational considerations reported in previous studies. Finally, the chapter concludes with key insights and recommendations for future research, providing a consolidated understanding of the current state of ORC WHR technology and its practical implications for achieving regulatory compliance and decarbonization targets in the shipping industry.

2. Waste Heat Onboard Ships

Onboard ships, the main propulsion engines are by far the largest single source of waste heat. A slow- or medium-speed diesel typically converts only about 45–50 % of the fuel's chemical energy into mechanical work at the crankshaft, with the remainder rejected as heat (Singh & Pedersen, 2016). The biggest portion of this loss leaves with the exhaust gases at 250–450 °C, representing roughly one-third of the fuel input. Another substantial share is carried away by the jacket cooling water, lubrication oil coolers, and charge-air coolers, usually at 60–90 °C, before being dissipated. According to the data obtained from CEAS (MAN, 2020), the heat load distribution of an 8600 kW engine (@100 MCR) powered by marine diesel oil and equipped with SCR system is shown in Figure 1. At full load, the engine exhibits a thermal efficiency of 50.9%. The remaining heat is distributed as 3.9% to lubricating oil, 7.8% to jacket cooling water, 18.7% to scavenge air, and 18.7% to exhaust gas.

Besides, as shown in Figure 2, the exhaust gas temperature starts relatively high, about 250–260 °C at low engine loads (25–40%), and then steadily decreases as the load increases, reaching roughly 200 °C around 70% load. This trend reflects the combined effects of increasing scavenge air flow and improved combustion efficiency at higher loads, which cool the exhaust stream despite greater fuel input. Beyond about 75% load, the temperature levels off and then shows a slight rise again toward full load (around 220 °C at 100% load), indicating that the higher fuel energy input begins to outweigh the cooling effect of additional air. This behaviour is characteristic of large marine diesel engines and has implications for the available energy for exhaust gas heat recovery systems.

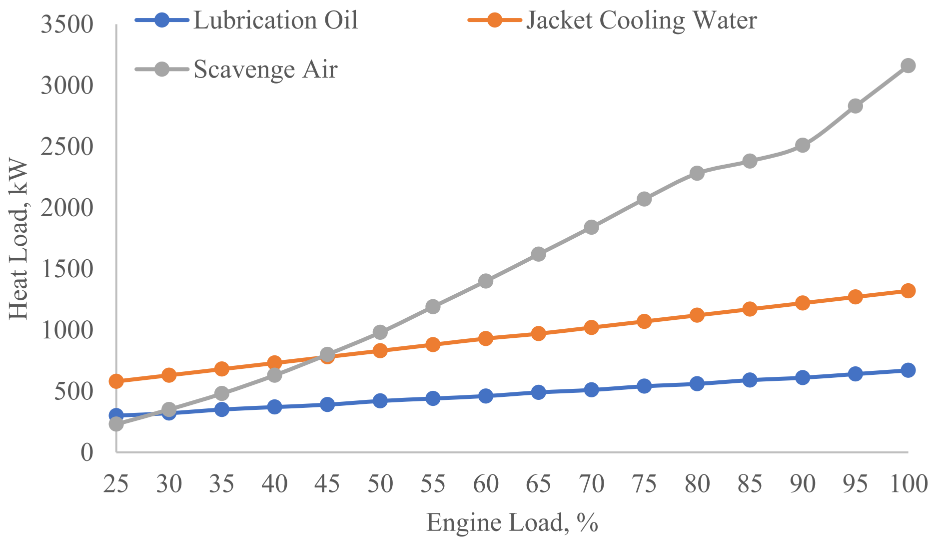

Figure 1. The heat load of waste heat sources in the main propulsion engine.

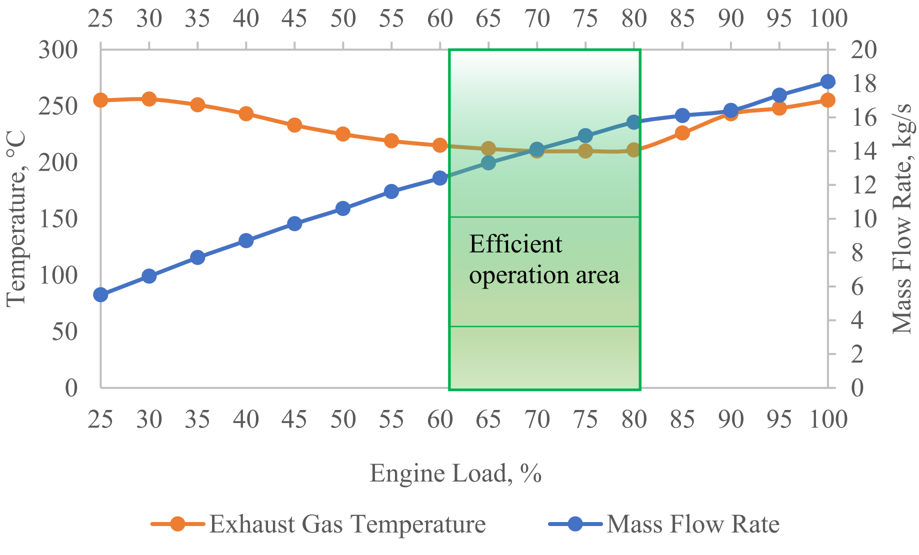

Figure 2. Mass flow rate and exhaust gas temperature of the exhaust gas.

The waste heat analysis shows that a huge amount of (>8000 kW) heat is dissipated via exhaust gas and cooling. However, the quality of waste heat from shipboard systems is significant, and it is primarily determined by the temperature, since temperature dictates both the usable energy content and the thermodynamic potential for recovery. High-temperature sources such as exhaust gases generally offer the best quality waste heat because they allow for higher efficiency in energy recovery processes like steam or Organic Rankine Cycles (Singh & Pedersen, 2016). Medium-temperature streams such as scavenge air or jacket cooling water contain substantial amounts of heat but at lower exergy (usable work potential), making them more suitable for low-temperature recovery technologies or preheating applications (Akman & Ergin, 2023; Song, Song, & Gu, 2015). Lubricating oil and other low-temperature fluids typically provide only limited recovery opportunities because their low temperatures restrict conversion efficiency. In practice, the hierarchy of waste heat sources on a marine engine mirrors their temperatures: the hotter the source, the higher its "quality" in terms of potential for useful energy recovery.

3. Working Fluid Selection

Selecting a working fluid is one of the most critical steps in designing an Organic Rankine Cycle (ORC) waste heat recovery (WHR) system, because the fluid's thermophysical properties directly influence efficiency, safety, and environmental impact (Akman & Ergin, 2022; Mondejar et al., 2018) as shown in Figure 3. The fluid must have a boiling point and critical temperature well matched to the heat source so that it can absorb and transfer energy effectively without excessive superheating or throttling losses (Fang, Yang, & Zhang, 2019). High thermal stability and low viscosity are crucial for minimizing degradation and reducing pumping power, while a favorable heat transfer coefficient enhances the performance of both the evaporator and condenser.

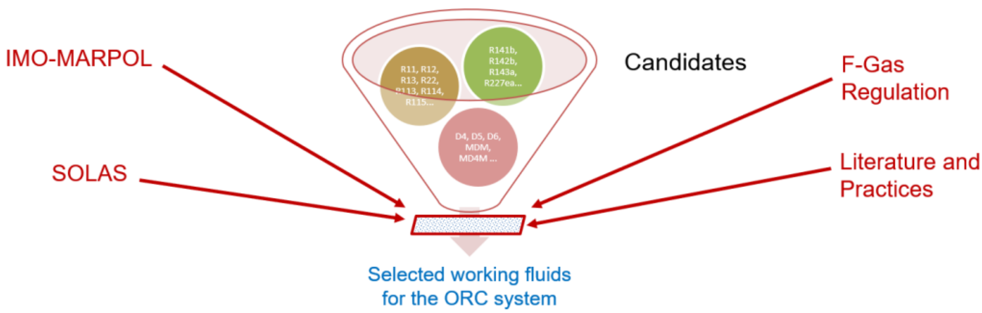

Figure 3. Filtering mechanism of working fluids to be selected for the shipboard ORC waste heat recovery systems

Safety and regulatory factors—such as flammability, toxicity, ozone depletion, and global warming potential—also significantly influence the selection process, especially in marine applications where environmental standards are stringent. According to MARPOL Annex VI, refrigerants with an ozone depletion potential greater than zero are prohibited, while under the F-Gas

Regulation, refrigerants with a global warming potential exceeding 2500 are progressively restricted (Akman, 2021; Mondejar et al., 2018). In practice, designers compare candidate fluids using performance indicators like thermal efficiency, exergy destruction, net power output, and compatibility with system materials. A well-chosen working fluid maximizes the usable energy recovered from the available waste heat while ensuring compliance with environmental regulations.

Hydrocarbons, hydrofluorocarbons (HFCs), and hydrofluoroolefins (HFOs) are three major classes of fluids considered for Organic Rankine Cycle (ORC) systems, each with distinct advantages and limitations in terms of safety, toxicity, and environmental performance. Hydrocarbons such as propane and butane offer excellent thermodynamic properties and very low global warming potential (GWP) with zero ozone depletion potential (ODP), but their high flammability imposes strict safety requirements in marine applications (Mondejar et al., 2018; Song & Gu, 2015). HFCs like R245fa and R134a are non-flammable and relatively non-toxic, which makes them attractive from a safety perspective; however, they possess high GWPs and thus face increasing regulatory restrictions (Dawo et al., 2021). HFOs such as R1233zd(E) and R1234ze(Z) represent a newer generation of working fluids with low GWPs and zero ODP, while maintaining non-flammable or mildly flammable classifications and generally low toxicity (Akman & Ergin, 2025; Dawo et al., 2021). In selecting a fluid for ORC waste heat recovery, designers must balance the relation between thermodynamic performance, system safety, and compliance with environmental regulations, with a shift toward low-GWP, zero-ODP alternatives such as HFOs as standards tighten. Table 1 shows the candidate working fluids and their properties for shipboard ORC WHR applications.

Table 1. Some of the candidate working fluids for the onboard ORC systems.

Working fluids	Normal boiling point (°C)	Critical temperature (°C)	Critical pressure (kPa)	GWP	ODP
R1233zd(E)	18.263	166.45	3623	1	0
R1234ze(Z)	9.728	150.12	3530	7	0
R1224yd(Z)	14.617	155.54	3337	1	0

R1336mzz(Z)	33.453	171.35	2903	2	0
R1234ze(E)	-18.973	109.36	3634	6	0
R152a	-24.023	113.26	4516	138	0
RE347mcc	34.178	164.55	2478	530	0
RE245cb2	5.61	133.66	2886	680	0
R245ca	25.13	174.42	3925	693	0
RE143a	-23.578	104.77	3635	756	0
R365mfc	40.15	186.85	3266	782	0
RE245fa2	29.25	171.73	3433	812	0

4. Orc Waste Heat Recovery Systems

The research and applications regarding onboard ORC WHR systems mainly focus on design and optimization. The exhaust gas is the major heat source based on its higher quality and energy content compared to other waste heat sources. Scavenge air cooling water, or jacket water waste heat sources are also used for very-low-grade waste heat recovery applications. Some of the ORC WHR configurations inspired by the previous studies (Akman & Ergin, 2023, 2025; Song et al., 2015; Yang, 2016) are shown in Figures 4-6. In these studies, hydrofluorocarbons (e.g., R245fa, R236ea, R365mfc), hydrocarbons (e.g., R601a, R600a), and hydrofluoroolefins (e.g., R1234ze, R1233zd(E), R1336mzz(Z), R1234yf) were used as working fluids. The results indicate that the thermal efficiency of exhaust gas-driven ORC systems typically ranges from approximately 14% to 20%, while ORC systems utilizing scavenge air or jacket cooling water achieve efficiencies of about 8% to 12%. Furthermore, depending on the ORC configuration and operating conditions, the overall efficiency of the power generation system can be improved by 1% to 5%. Selected real-world applications of ORC-based waste heat recovery systems onboard ships are discussed below.

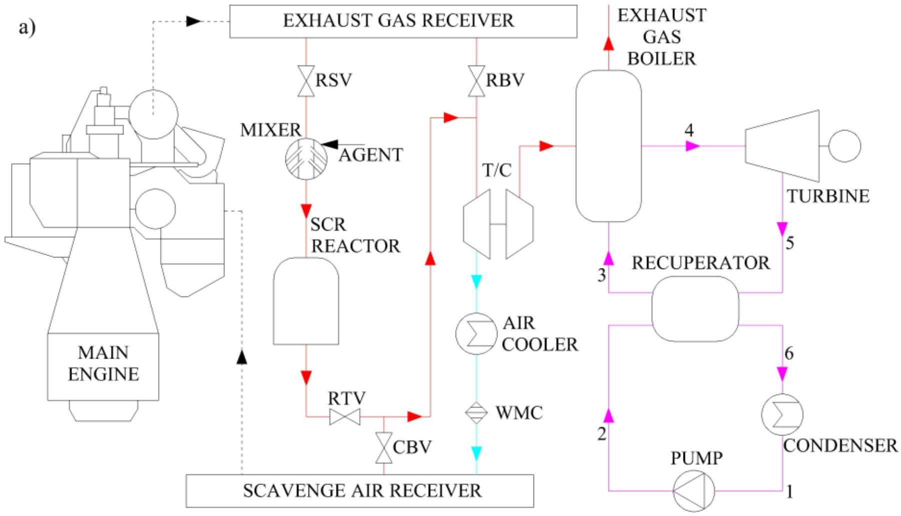

Figure 4. Schematic diagram of a recuperative exhaust gas WHR system integrated with an EGR-equipped marine engine.

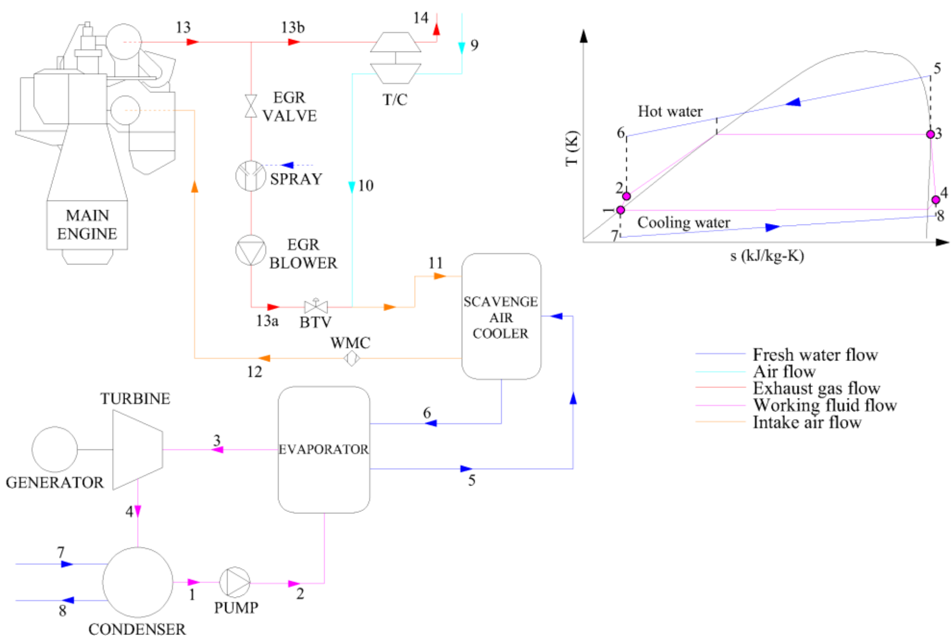

Figure 5. A schematic diagram of a scavenge air driven waste heat recovery system integrated with an EGR-equipped marine engine.

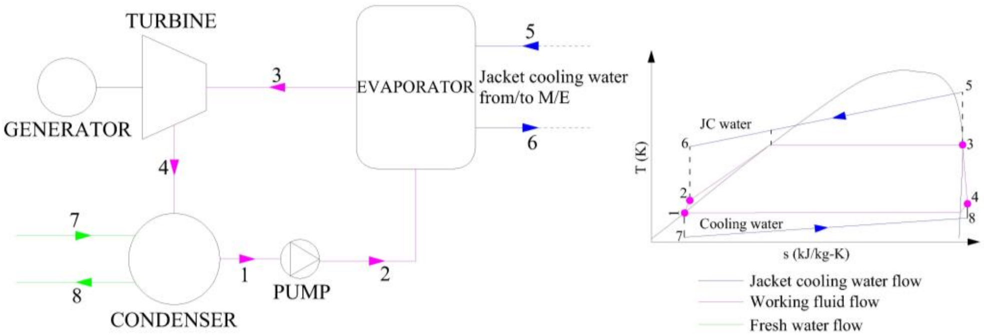

Figure 6. A schematic diagram of a jacket cooling water waste heat recovery system integrated with an EGR-equipped marine engine.

Opcon, in partnership with Wallenius Marine and supported by the Swedish Energy Agency, completed its first ocean-going installation of ORC Waste Heat Recovery technology (up to 800 kW), which was first and officially approved by Lloyd's Register for maritime use, as shown in Figure 4 (Green Car Congress, 2012). The system converts low-grade waste heat from a vessel's steam and cooling circuits into electricity, aiming to reduce fuel consumption and emissions of CO_2, NO_X, sulfur, and particulate matter. On the Car-Truck Carrier MV Figaro, the technology is projected to achieve fuel savings of 4–6%, with Opcon estimating a potential 5–10% reduction in other applications (Green Car Congress, 2012).

Figure 7. The MV Figaro and Opcon Powerbox ORC WHR system.

Mitsubishi Heavy Industries launched its ORC Module aboard the Maersk Line vessel Arnold Maersk in 2016, as shown in Figure 8. It is reported (MHI, 2016) that the system converts very low-temperature waste heat, specifically from the main engine jacket cooling water (~85°C), into electricity, reducing the load on the vessel's main generator while lowering CO_2 emissions and enhancing overall plant efficiency. Delivering 125 kW, the ORC was previously validated through pilot testing at Calnetix Technologies and received ClassNK approval in 2015.

Figure 8. The Arnold Maersk and 125 kW – ORC jacket cooling water WHR.

5. Conclusions

This chapter points out that Organic Rankine Cycle (ORC) waste heat recovery technology offers significant potential for enhancing energy efficiency and reducing emissions in maritime operations. By evaluating waste heat sources such as exhaust gases, jacket cooling water, and scavenge air, and by assessing the suitability of various working fluids based on efficiency, environmental impact, and safety, the review provides a clear framework for implementing ORC systems onboard ships. The analysis of different ORC configurations and their operational performance highlights both the opportunities and challenges of integrating these systems with marine engines. Importantly, the adoption of ORC WHR systems can contribute to improved Energy Efficiency Design Index (EEDI) and Energy Efficiency Existing Ship Index (EEXI) compliance, as well as reduced Carbon Intensity Indicator (CII) ratings, supporting regulatory targets and accelerating the decarbonization of the shipping industry. Future research in marine ORC waste heat recovery should focus on onboard real-time monitoring, control strategies, and predictive frameworks that can improve reliability and optimize power output under varying operational conditions.

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CHAPTER 4

MARITIME TRANSPORT AND OCEAN POLLUTION: EMERGING CHALLENGES AND INTERNATIONAL LEGAL APPROACHES

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Abstract

Maritime transport forms the backbone of global trade, yet it imposes substantial environmental pressures on marine ecosystems. Ship operations generate chemical, biological, and physical pollution through oil spills, bilge and ballast discharges, solid waste release, and exhaust emissions. Major tanker accidents and chronic illegal bilge dumping contribute to persistent hydrocarbon contamination, whereas ballast waters serve as a primary vector for invasive species introduction across oceans. Plastic waste and lost fishing gear originating from ships pose severe threats to marine mammals, birds, and fish through ingestion and entanglement. Additionally, ship exhaust emits greenhouse gases, sulfur oxides, nitrogen oxides, and particulate matter, degrading air quality and threatening human health. Toxic compounds used in antifouling coatings accumulate in sediments and adversely affect benthic organisms. International regulatory frameworks, particularly the LOSC and MARPOL annexes, establish essential mechanisms to control these impacts. However, in the context of expanding maritime trade and climate-driven pressures, the reinforcement of existing measures and effective enforcement remain indispensable to safeguard marine environmental integrity at a global scale.

Keywords: Maritime pollution, Shipborne emissions, Ballast water management, Antifouling toxicity, Marine environmental regulation.

1. Introduction

Maritime transport constitutes the backbone of global trade, while concurrently generating multifaceted environmental risks. Various forms of pollution enter the marine environment as a result of ship operations and accidents, including oil spills, waste discharges, harmful exhaust gases, and toxic substances released from hull coatings. Scientific studies conducted over the past decade have revealed significant findings regarding the cumulative impacts of ship-based pollution on marine ecosystems and biodiversity (Al-Kamzari et al., 2025; Calgaro et al., 2025). These pollution types affect not only the local environment but also ocean-scale habitats and species populations; moreover, they may harm human health through seafood consumption and negatively impact coastal economies (e.g., fisheries, tourism) (Ellos & Bacosa, 2025; Al-Kamzari et al., 2025).

To understand the magnitude of ship-generated pollution, it is necessary to consider the global scale of maritime activities. According to data from the International Maritime Organization (IMO), as of 2018 maritime transport accounted for approximately 2.9% of global carbon emissions (1.076 billion tons of CO_2 annually) (European Commission, *Reducing Emissions from the Shipping Sector – Climate Action*, https://climate.ec.europa.eu/eu-action/transport-decarbonisation/reducing-emissions-shipping-sector_en). Additionally, ships represent a significant share of certain pollutant categories: for instance, in Europe, maritime transport accounted for 24% of total anthropogenic NOx (nitrogen oxides) emissions and 24% of SOx (sulfur oxides) emissions in 2018 (European Environment Agency & European Maritime Safety Agency, 2021). Ship wastes and discharges also contribute to marine litter and chemical pollution. Although the majority of plastic marine debris originates from land-based sources (estimated at approximately 80%), waste discharged from vessels and fishing activities constitute a substantial portion of the remaining share (Jambeck et al., 2015). Scientific research has demonstrated that ship activities introduce significant amounts of pollutants into the marine environment, including heavy metals such as copper and zinc (from antifouling paints), nitrogenous compounds (from ship-generated wastewater), and polycyclic aromatic hydrocarbons (PAHs; from fuel and exhaust emissions) (Calgaro et al., 2025).

This chapter compiles and presents ship-generated pollution types and their environmental impacts, drawing upon scientific literature from the past decade.

2. Types of Ship-Generated Pollution

2.1. Oil and hydrocarbon pollution

One of the most visible and detrimental forms of pollution associated with maritime transport is the introduction of oil and other hydrocarbons into the marine environment. This pollution generally arises through two main pathways: (1) large-scale spills caused by major accidents (such as tanker disasters, vessel collisions, and groundings), and (2) operational or small-scale discharges (including waste oil, bilge water, and fuel leakages generated during routine ship activities). Although the number of major tanker accidents and the volume of spilled oil have demonstrated a decreasing trend over the past 20 years, significant incidents still occur periodically and result in severe environmental consequences (Al-Kamzari et al., 2025; Barron et al., 2020). Large-scale spills typically involve the release of crude oil or fuel cargo into the sea; for instance, in the 2010 Deepwater Horizon disaster (Gulf of Mexico) and the 2007 Hebei Spirit incident (South Korea), millions of liters of oil were discharged into the marine environment (Barron et al., 2020).

Conversely, small-scale and recurrent oil pollution represents a widespread problem within maritime operations. Bilge waters and oily wastes produced during ship machinery and cargo handling processes may be discharged into the sea when appropriate treatment systems or port waste reception facilities are not utilized. Research has indicated that commercial fleets discharge an estimated 810,000 tons of oily bilge water and sludge into the world's oceans annually (Al-Kamzari et al., 2025). These illegal and unauthorized discharges are typically conducted in offshore areas and during times when detection is difficult—such as at night—and although each incident may not attract the same attention as a major accident, they cumulatively create severe pollution impacts on coastal ecosystems (Al-Kamzari et al., 2025). Because bilge and fuel leakages often cannot be attributed to a particular vessel unless detected by specialized sensors, they are also referred to as "unattributable pollution," a circumstance that enables perpetrators to evade penalties (Al-Kamzari et al., 2025).

Tanker accidents constitute some of the most prominent examples of oil and hydrocarbon pollution. Türkiye has also witnessed significant incidents in its recent maritime history: for instance, the 1994 Nassia tanker accident in the Istanbul Strait resulted in tens of thousands of tons of crude oil being discharged into the sea, causing a massive fire and extensive damage to coastal ecosystems (Usluer & Alkan, 2016). In the past decade, smaller-scale but similar events have occurred. In January 2017, approximately 90–100 tons of petroleum product leaked into the Gulf of İzmit due to overflow from an industrial fuel storage facility, only 60 tons of which could be recovered (Heinrich-Böll-Stiftung e.V., 2017). Likewise, in December 2016, 200 tons of diesel fuel were spilled off the coast of İzmir following the grounding of a vessel, and the leakage could not be fully contained for more than a week (Heinrich-Böll-Stiftung e.V., 2017). Such incidents pose significant ecological threats, particularly in semi-enclosed and sensitive marine areas such as the Sea of Marmara and the Aegean Sea. For example, the 2017 İzmit Gulf spill occurred near ecologically sensitive areas, including the Ramsar-protected Hersek Lagoon bird sanctuary, raising considerable concern (Heinrich-Böll-Stiftung e.V., 2017).

2.2. Bilge and ballast waters

Bilge waters generated onboard ships consist of oily water mixtures accumulating in the engine room and must be properly treated and stored. Although bilge water is typically processed through oil–water separators to reduce its oil content to below 0.05% (50 ppm) before controlled discharge into the sea in accordance with MARPOL Annex I, many vessels unfortunately disregard these regulations by directly pumping bilge water overboard or falsifying waste logs (Al-Kamzari et al., 2025). As noted above, this practice leads to small yet persistent oil pollution. Moreover, detergents, chemicals, and heavy metals contained in bilge waters may also enter the marine environment, deteriorating water quality.

Ballast water, on the other hand, consists of seawater taken onboard by ships to maintain stability. These waters—taken from and discharged at different ports during loading and unloading operations—pose a particular environmental concern: the transfer of non-native biological organisms. Through ballast water, ships can transport plankton, larvae, bacteria, and other organisms from one port to another thousands of kilometers away. Over the past 50 years, ballast waters have been identified as one of the primary vectors for the spread of numerous invasive species observed in the world's oceans (Ghabooli et al., 2013; Scherman, 2023). In these newly introduced environments, such invasive organisms may rapidly proliferate in the absence of natural predators, suppress native species, reduce biodiversity, and cause major economic losses.

A historically notable example is the introduction of the Atlantic-origin ctenophore *Mnemiopsis leidyi* (commonly referred to as the comb jelly) into the Black Sea via tanker ballast water in the 1980s (Ghabooli et al., 2013). This invasive species experienced a dramatic population explosion in the Black Sea, leading to declines of up to 90% in anchovy (*Engraulis encrasicolus*) and sprat (*Sprattus sprattus*) stocks, effectively causing the collapse of regional fisheries (Scherman, 2023).

In summary, bilge and ballast water discharges not only introduce oil, chemical contaminants, and nutrient loads into the marine environment but also contribute to biological contamination (bio-pollution). Therefore, it is critically important to properly remove oil from bilge waters and to ensure that ballast waters are appropriately treated prior to discharge or exchanged in open ocean waters.

2.3. Solid wastes and marine litter

The generation of solid waste during ship operations is inevitable: waste generated by crew and passengers (food residues, packaging materials), materials resulting from ship maintenance and repair, and cargo residues and spillages, among others. Some of this waste is incinerated onboard or delivered to port reception facilities; however, for many years ships disposed of their waste directly into the sea. Following the entry into force of MARPOL Annex V (Regulations for the Prevention of Pollution by Garbage from Ships) in 1988, the discharge of plastics into the sea was completely prohibited, and restrictions based on distance from shore and specific conditions were imposed for other waste types. Despite this legal framework, plastic packaging wastes, synthetic ropes and nets, and food wastes are still discarded into the sea in practice. Moreover, a substantial amount of solid material may enter the marine environment due to incidents such as container loss during severe weather. For example, the burning and subsequent sinking of the vessel *X-Press Pearl* off Sri Lanka in May 2021 resulted in the release of massive quantities of plastic raw material (nurdles) and chemicals into the ocean, leading to months-long plastic pellet pollution along regional coastlines (Rist et al., 2025).

Plastics are the largest component of marine litter. Because plastics do not biodegrade and can travel long distances, they accumulate throughout the world's oceans. Research indicates that more than 80% of plastics entering the marine environment originate from land-based sources, transported via rivers and coastal activities (Jambeck et al., 2015). However, ship-generated waste and, in particular, the loss of fishing gear (nets, ropes) constitute a significant portion of the remainder. It has been estimated that approximately 4.8 to 12.7 million tons of plastic entered the oceans from land in 2010 (Jambeck et al., 2015). Surveys conducted in ocean garbage accumulation zones and coastal dunes report that 75–85% of collected debris consists of plastic materials (Rhodes, 2018). Ship-generated wastes include plastic bottles, packaging, polystyrene materials, metal cans, glass bottles, and organic refuse. Although organic food waste and biodegradable materials such as paper do not create persistent environmental problems to the same extent as plastics, plastic pollution poses a serious threat to marine life. Many species, such as whales, seabirds, and sea turtles, ingest floating plastics mistaken for food, leading to intestinal blockage or starvation. Additionally, discarded fishing nets and ropes entangle marine mammals and fish (ghost fishing), causing injuries and fatalities.

To prevent ship-sourced solid waste pollution, each vessel is required to maintain a Garbage Management Plan and to store and deliver its waste to port facilities. Although many ports provide such services, practical shortcomings persist. Nonetheless, on a global scale, since the enforcement of MARPOL Annex V, the once-common practice of large passenger ships discharging tons of garbage directly into the sea has declined, and some improvement has been observed in the reduction of marine litter from ships (Jambeck et al., 2015).

2.4. Exhaust emissions (air pollution)

Fossil fuels burned in ship engines and boilers (primarily high-sulfur fuels such as fuel oil and marine diesel) release combustion products into the atmosphere, contributing to air pollution and climate change. International maritime transport accounts for approximately 2.5–3% of global greenhouse gas (CO_2) emissions, making it a significant carbon source (European Commission, 2025). In 2018, CO_2 emissions from international shipping reached approximately 1.1 billion tons, and projections indicate that, without mitigation measures, these emissions could increase by more than 90% by 2050 (European Commission, 2025). Ship exhaust gases also contain sulfur oxides (SOx), nitrogen oxides (NOx), carbon monoxide, volatile organic compounds, and particulate matter (PM). When high-sulfur fuels are used (for example, 3.5% sulfur fuel oil), the resulting SO_2 and SO_3 emissions release substantial amounts of sulfur into the atmosphere. Until 2020, international ships operating on the high seas were allowed to use fuels with sulfur content up to 3.5%—significantly higher than limits permitted for land-based fuels. Under new regulations adopted pursuant to MARPOL Annex VI, the sulfur limit for marine fuels was reduced to 0.50% as of January 1, 2020 (IMO 2020 sulfur regulation). This measure is expected to reduce total SOx emissions from ships by 77%, equivalent to approximately 8.5 million tons less SOx released annually (International Maritime Organization, 2025).

Air pollutants originating from ships have multiple impacts on human health and the environment. Sulfur oxides and nitrogen oxides combine with atmospheric water vapor to form acid rain, which acidifies forests, freshwater bodies, and marine surface waters, adversely affecting ecosystems (International Maritime Organization, 2025). In particular, SOx emissions contribute to the acidification of ocean surface waters, harming coral reefs and shell-forming marine organisms (International Maritime Organization, 2025). A health impact assessment estimated that, had the 2020 sulfur regulation not been implemented, ship-generated air pollution could have resulted in an additional 570,000 premature deaths globally between 2020 and 2025 (International Maritime Organization, 2025).

Regionally, narrow straits and port cities with dense maritime traffic are most affected by ship emissions. For instance, approximately 40,000 vessels transit the Istanbul Strait annually, many of which are high-tonnage ships and tankers (Ilicali, 2021). Emission estimates indicate that ships passing through the Strait annually release approximately 18,300 tons of NOx, 5,300 tons of SOx, 937,000 tons of CO_2, and 692 tons of PM into the atmosphere over Istanbul (Ilicali, 2021).

Over the past decade, the IMO, the European Union, and other authorities have taken several steps to reduce air emissions from ships. In addition to lowering sulfur limits, certain maritime regions have been designated as Emission Control Areas (ECAs) where stricter standards apply. In ECAs such as the Baltic Sea, the North Sea, and the U.S.–Caribbean regions, the sulfur limit is 0.10% (International Maritime Organization, 2025).

2.5. Antifouling paints and toxic chemicals

Antifouling paints used on ship hulls, propellers, and other submerged surfaces to prevent the accumulation of organisms such as algae, mussels, and fish eggs represent another dimension of ship-generated chemical pollution. These coatings gradually release biocidal (organism-killing) chemicals upon contact with seawater, thereby preventing the settlement of marine organisms on vessel surfaces. Historically, the most widely used and effective antifouling agents were organotin compounds, particularly tributyltin (TBT). TBT-based coatings became widespread beginning in the 1960s; however, starting in the 1970s, their extreme toxicity became increasingly evident. Even at very low concentrations, TBT induces a condition known as imposex—masculinization and reproductive disruption—in sensitive species such as marine gastropods (Wikimedia Foundation, 2025, Imposex). Consequently, the IMO adopted the International Convention on the Control of Harmful Anti-Fouling Systems on Ships in 2001, which led to the global ban of TBT on all vessels as of 2008 (Wikimedia Foundation, 2025, Imposex).

Following the prohibition of TBT, copper-based antifouling paints have become predominant. Although copper-based coatings are not as destructive as TBT, their continuous use leads to copper accumulation in harbor waters, particularly in enclosed and low-circulation environments such as marinas. Copper is a toxic heavy metal for aquatic organisms at elevated concentrations; it can cause gill damage in fish and impair reproduction and growth in invertebrates. Scientific studies have demonstrated that copper rapidly binds to sediments in the marine environment and accumulates there, negatively affecting the diversity of benthic (bottom-dwelling) organisms (Jamal & Shi, 2023).

3. International Regulations and Legal Framework

Linné and Svensson (2015) describe the international framework applied for the regulation and control of ship-sourced pollution as follows: the fundamental legal basis in the field of maritime law is the 1982 United Nations Convention on the Law of the Sea (LOSC). This convention defines the rights and obligations of flag States, coastal States, and port States for each maritime zone. The general principle is as follows: the closer a vessel is to the coast, the greater the legislative and enforcement jurisdiction of the coastal State; the farther away it travels, the more such authority diminishes. LOSC establishes the foundational structure that determines legislative authority corresponding to the maritime zones of coastal States and their obligations to protect the marine environment. MARPOL 73/78 is the principal international convention aimed at preventing operational and accidental pollution from ships. In conjunction with the 1982 LOSC, detailed technical standards are prepared by the IMO and incorporated into the LOSC framework through reference rules. The convention applies to ships flying the flag of a State Party as well as vessels flying the flag of non-Party States when they enter the ports of a Party State. Warships and naval auxiliary vessels are excluded from the scope of application. Violations are prohibited regardless of where they occur; sanctions are applied according to the domestic laws of the State whose flag the vessel flies. Through port State control mechanisms, provisions may also be applied to ships flying the flag of non-Party States.

MARPOL contains six annexes, introduced at different times, that collectively provide the regulatory structure necessary to control pollution from ships.

The principal MARPOL annexes are as follows:

• **Annex I: Prevention of Pollution by Oil and Oil Products** (in force since 2 October 1983): Aims to regulate both operational and accidental oil pollution from ships. A 1992 amendment introduced the requirement for double-hulled oil tankers and established a phased transition period for implementation.

• **Annex II: Noxious Liquid Substances in Bulk** (entered into force on 2 October 1983; provisions effective as of 6 April 1987): Establishes discharge criteria and preventive measures for ships carrying harmful liquid substances. In this context, approximately 250 chemical substances have been evaluated and incorporated into the convention.

• **Annex III: Harmful Substances Carried in Packaged Form** (in force since 1 July 1992): Contains packaging, labeling, and handling rules designed to minimize environmental harm in the event of leakage of packaged hazardous materials (e.g., containers, drums). This annex aims to reduce cargo-based pollution risk.

• **Annex IV: Sewage Discharge from Ships** (in force since 27 September 2003): Regulates the discharge of sewage from ships. Requirements include the installation of approved treatment systems or discharge at least 12 nautical miles offshore while underway.

• **Annex V: Garbage and Solid Waste** (in force since 31 December 1988): Regulates the disposal of garbage from ships. The discharge of plastics into the sea is strictly prohibited; disposal of other wastes such as paper, glass, and metal is restricted according to distance from shore (subject to specified conditions). Ships are required to maintain a garbage record book. Annex V was revised in 2013 to expand and tighten requirements for the management of all waste types (including organic waste other than food scraps).

• **Annex VI: Air Pollution (Exhaust Emissions)** (in force since 19 May 2005): Limits sulfur content in marine fuels, establishes NOx emission standards, prohibits shipboard use of ozone-depleting substances (e.g., older refrigerants), and promotes fuel-efficiency measures. For example, the global 0.50% sulfur limit effective from 2020 falls under Annex VI (imo.org).

In addition to MARPOL, several other significant international conventions address ship-sourced pollution:

• **International Convention on the Control of Harmful Anti-Fouling Systems on Ships (AFS Convention, 2001/2008)**: Prohibits the use of antifouling paints containing harmful chemicals.

• **International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM Convention, 2004/2017)**: Sets regulations for the treatment of ballast water prior to discharge. The convention includes various measures aimed at preventing the transfer of living organisms between ecosystem.

• **Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships (2009 / in force 2025)**: Establishes requirements and standards for ship-recycling facilities to minimize environmental and human-health impacts.

• **Nairobi International Convention on the Removal of Wrecks (2007/2015)**: Specifies rules concerning the removal of wrecks that pose environmental risks.

4. Conclusion

In conclusion, combatting ship-sourced pollution requires a multifaceted effort: robust legislation, effective enforcement, advanced technological measures, proactive industry participation, and international cooperation must progress in tandem. Although significant progress has been achieved over the past decade, continued and expanded efforts are essential to protect the marine environment amid the pressures of climate change and increasing maritime traffic. Türkiye, as a country directly affected by marine pollution due to its geographic position, should play an active role in global initiatives while safeguarding its own maritime jurisdiction. Our seas are a shared heritage; reducing all pollution loads—whether ship-generated or otherwise—is a collective responsibility of humanity. Ensuring a balanced harmony between the transport sector and environmental management will make it possible to leave cleaner seas to future generations, supporting a healthy and sustainable marine environment.

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CHAPTER 5

A STUDY ON FLOATING DOCKS: INVESTMENT, OPERATION, AND SAFETY ASPECTS

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Abstract

Floating docks are essential facilities in ship repair and maintenance, as they allow underwater hull inspections and repairs without the need for permanent land-based structures. This paper outlines the general characteristics and working principles of floating docks, with particular attention to their advantages, operational processes, and safety considerations. The study discusses planning aspects of floating dock investments, highlighting technical, economic, and regulatory factors. Additionally, operational steps during docking and undocking are presented alongside sample checklists, emphasizing the importance of standardized procedures for ensuring both vessel and dock safety. A review of recent floating dock accidents further illustrates the potential vulnerabilities associated with stability management, particularly failures in ballast systems and valves. By integrating regulatory references, sector reports, and selected examples from past incidents, the paper aims to provide a comprehensive overview of floating dock practices and the critical issues that should be addressed for safe and efficient operations.

Keywords: Floating docks, ship repair and maintenance, docking and undocking operations.

1. Introduction

The ship repair and maintenance sector plays a critical role in ensuring the uninterrupted continuity of maritime operations. One of the most important infrastructure elements in this sector is the docking facilities, which enable hull maintenance by separating the ship from the sea. These facilities can generally be divided into two categories: land-based and floating. In the English literature, the general term “dry dock” is used to describe docking facilities. Floating structures are typically referred to as floating dry docks or floating docks, while land-based facilities are described as graving docks or graving dry docks. Similarly, Turkish regulatory documents and sectoral reports employ varying expressions. For instance, in the *Regulation on Shipyards, Boat Building and Boatyards (In Turkish: Tersane, Tekne İmal ve Çekek Yeri Hakkında Yönetmelik)* (T.C. Ministry of Transport and Infrastructure, 2015) and in the Türk Loydu Rules, Part A - Rules for Hull, Material and Welding, Chapter 1 Hull (Türk Loydu, 2024), the terms “yüzer havuz” (floating dock) and “kuru havuz” (dry dock) are used. Likewise, in the sector report of the Turkish Shipbuilders’ Association (GİSBİR), “yüzer havuz” (floating dock) is employed for floating docking structures, and “kuru havuz” (dry dock) is used for land-based docking structures (Türkiye Gemi İnşa

Sanayicileri Birliği, 2022). Based on an evaluation of these usages, in this study the term “floating dock” is preferred for floating structures, while “graving dock” is preferred for land-based facilities.

Floating docks are essential facilities for carrying out maintenance and repair work on the ship’s bottom. These structures are large-scale installations, with their size determined by the dimensions of the vessels they are designed to accommodate (Korotaev et al., 2016). Through the use of floating docks, operations such as hull cleaning, steel work repairs, and maintenance of propellers and rudders can be performed efficiently and safely.

The global shipping fleet continues to grow, with vessel sizes steadily increasing. For instance, the carrying capacity of container ships rose from 3.17 million TEU in 1990 to 18.9 million TEU in 2014, while the capacity of the largest container ships expanded from 4,300 TEU to 18,000 TEU over the same period (Tran & Haasis, 2015). In addition, issues such as environmentally responsible operations and energy efficiency are key factors to be considered in floating dock investments, particularly in recent years (Rosochowicz & Łącki, 2005; Szelangiewicz et al., 2023).

Floating docks offer greater flexibility compared to graving docks. They can operate by being moored at suitable locations in shipyards and, thanks to their mobility, can be deployed according to regional needs. However, alongside these advantages, there are many technical and administrative aspects that must be considered in the planning, operation, and classification of floating docks. In addition, the construction costs of very large floating docks (e.g., post-Panamax class) are higher than those of graving docks of the same size (Lamb, 2003).

2. General Definition and Working Principle of Floating Docks

The Turkish Regulation on Shipyards, Boat Building and Boatyards defines a floating dock as “a marine vessel that can be used for ship construction, conversion, repair, maintenance, and even transportation” (T.C. Ministry of Transport and Infrastructure, 2015). Accordingly, floating docks are large maritime structures with their own lifting capacity, designed to carry out maintenance and repair work on the underwater of ships. They function as a kind of mobile graving dock. Unlike graving docks, floating docks can be completely submerged to receive a vessel and then refloated to lift the vessel above the waterline. In some cases, floating docks may also be used for newbuilding.

Floating docks are usually positioned along the shore and are designed with side walls and pontoons to provide the space needed for a vessel to settle. Typically constructed from steel, they can be built in various sizes and capacities.

The main components of a floating dock include side walls, pontoons, ballast tanks, pumping systems, cranes, and control and power systems. The ballast tanks located in the pontoons and side walls are used to submerge the dock and to adjust heel and trim balance. A simple cross-section of a floating dock is shown in Figure 1.

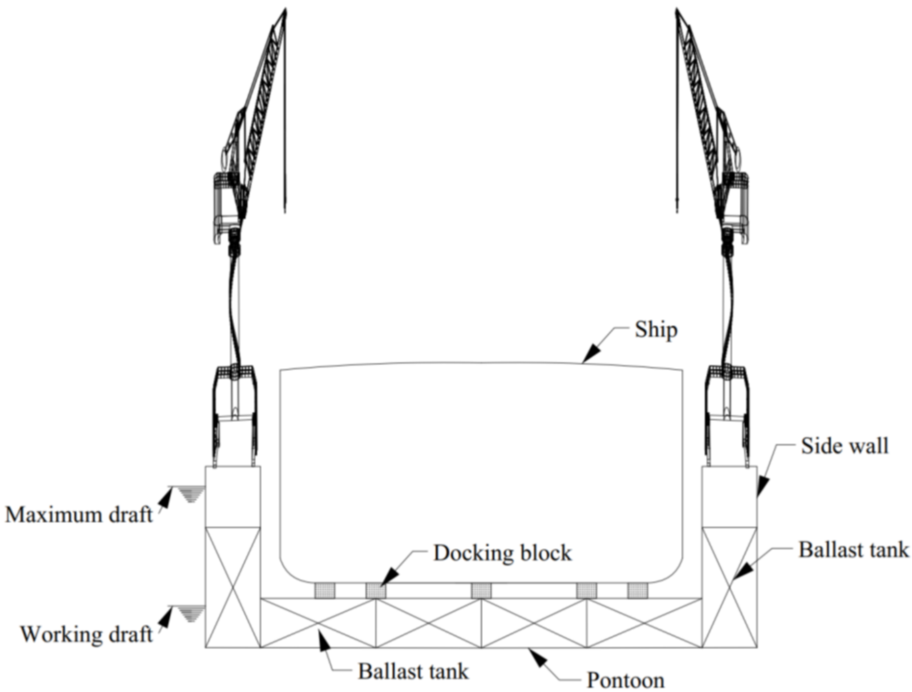

Figure 1. Schematic representation of a floating dock.

The operation of a floating dock is essentially based on Archimedes' principle. The dock submerges by filling its ballast tanks with water; after the vessel is positioned inside, the tanks are emptied to raise the dock and lift the ship above the waterline. The docking process can be summarized as follows: For submersion, the ballast tanks are filled with water, allowing the dock to sink in a controlled manner so the vessel can enter. Once the ship is properly aligned with the docking block system, the dock's balance is checked. To maintain stability, water is selectively pumped in or out of the ballast tanks to correct trim and heel. For lifting, the ballast tanks are emptied using pumps, causing the dock to rise and bring the ship above the water. This allows maintenance and repair work to be carried out on the bottom of the vessel. During these operations, two of the most critical concerns are deflection and stability of the dock. Improper balancing or excessive deflection can cause severe damage to both the ship and the dock. Indeed, past accidents have been reported due to such issues (Figure 2).

Figure 2. A floating dock broken at the midsection (URL1, URL2).

Floating docks are adaptable structures that can be relocated and integrated into shipyard infrastructure, offering significant advantages for ship repair and maintenance activities. They allow maintenance work to be completed more quickly, thereby improving the operational efficiency of vessels and extending their time at sea. However, their sensitivity to wave and currents introduces certain challenges in operation. Stability, in particular, must be carefully managed, as any imbalance can increase operational risks. In recent years, several incidents have highlighted the operational risks and vulnerabilities of floating docks. Even minor technical issues -such as valve malfunctions or ballast system failures- can lead to serious consequences, including instability, structural damage, or even total loss of the dock and vessels onboard. Table 1 summarizes some of the floating dock accidents, offering insight into the types of failures that have occurred and their underlying causes.

Table 1. Overview of floating dock accidents reported in recent years (Adapted from (Wen et al., 2024)).

Year	Country	Incident Summary
2012	USA	The dock developed an excessive list due to a malfunctioning valve, leading to its sinking along with the vessel on top.
2015	Poland	A faulty valve caused a ferry to slip off the keel blocks during docking operations.
2017	Poland	Loss of stability resulted in the dock heeling nearly 70° while carrying a tanker.
2018	Poland	A failure in the ballast system caused the dock to tilt and partially rest on the seabed.
2018	Denmark	The dock dramatically tilted with a fishing boat on board due to stability loss.
2018	Russia	A ballast pump failure led to the sinking of the dock, which also tore a large hole in the aircraft carrier's deck.
2019	Turkey	Overloading caused the dock to split in two, collapsing a crane and damaging the ships on board.

3. Planning Floating Dock Investments

As of 2022, Türkiye has 35 floating docks and 11 graving docks (Turkish Shipbuilders' Association, 2022). Investing in a floating dock is a high-cost, long-term decision for shipyards. Therefore, the investment process requires detailed analysis and planning. For businesses operating in shipbuilding and maintenance-repair, a floating dock provides both increased capacity and a competitive advantage. However, many factors affect the feasibility of this investment.

In the investment decision process, a market needs analysis should be conducted first. The number of ships operating in the region or potentially coming for maintenance and repair, their types, and tonnage ranges should be examined, and the floating dock capacity should be determined accordingly. In addition, a cost-benefit analysis, the return on investment, operating expenses, and amortisation calculations should be carried out.

Examining the technical suitability of the floating dock for the shipyard is also an important aspect. This means that the shipyard's existing infrastructure and the area where the floating dock will be placed should be assessed in terms of depth, currents, and port facilities. In addition, for compliance with legal regulations, approvals from official authorities and relevant procedures must be followed as part of the floating dock investment. Relevant regulations, such as the Regulation on Shipyards, Boat Building and Boatyards (T.C. Ministry of Transport and Infrastructure, 2015) and the Regulation on Environmental Management of Shipyards, Boat Building and Boatyards (T.C. Ministry of Environment, Urbanisation and Climate Change, 2022), along with other applicable legislation and authorities' rules, form part of the investment process. During this process, a risk analysis should also be conducted, taking into account economic fluctuations, technological developments, and operational risks.

One of the most critical aspects of floating dock investments is accurately and realistically estimating costs. These costs can generally be divided into investment costs and operating costs. Under investment costs, the first consideration should be how the floating dock will be acquired. At this point, a comparison between constructing a new dock and purchasing a second-hand dock is necessary. It should be noted that, due to the limited production of floating docks in the industry, existing docks are generally maintained through necessary repairs, and therefore, second-hand sales occur at very low levels (Harmoni Real Estate Valuation, 2024). In addition, transporting the dock to the shipyard, performing assembly if required, and related logistics directly affect the total investment budget. Moreover, integrating the floating dock into the shipyard's infrastructure is another significant cost item. This includes installing mooring systems, acquiring anchoring equipment, arranging piers, and, if necessary, dredging -all of which add to the total investment cost. Regarding operating costs, items such as personnel expenses, maintenance and class renewal costs, fuel and energy consumption, and insurance expenses should be considered.

4. Floating Dock Operations

The effective and safe use of floating docks depends on well-planned and standardized operational procedures. The process of docking ships into a floating dock is complex and challenging. Before the docking operation, certain preparations must be carried out both on the dock and on the ship to be docked. Carefully executing these procedures is critical for the safety of both the ship and the dock. Pre-docking tasks should be systematically checked using a document such as the Docking Preparation Audit, shown as an example in Table 2.

In ship docking, the docking block system must be properly designed and positioned to ensure the ship is safely supported and operations are carried out efficiently. The docking block system uses concrete blocks, steel structures, and wooden chocks on contact points with the ship's hull to create a soft surface (Figure 3).

After the ship is safely docked, it is necessary to check that it is fully supported on the docking blocks and that the side support elements are properly positioned. Then, the dock is drained just enough for the ship to rest securely on the docking blocks and for the dock floor to emerge, creating a suitable working environment for maintenance and repair. At this stage, the structural safety of both the ship and the dock is reviewed again. The operations carried out on the ship while in the dock can generally be listed as shown in Table 3.

Table 2. Example of a Pre-Docking Audit Form (Harren, 2010).

Item	Sub-item	Satisfactory	Unsatisfactory
Foundation Block: Timber	Check timber for excessive crushing, warping, cracking, rot, and degraded material	□	□
	Note amount of wear from fasteners	□	□
	Evaluate the condition of the interface between blocks in the stack	□	□
	Note condition of the fasteners in the blocks	□	□
	Note arrangements for preventing tripping and floating of blocks	□	□
Foundation Block: Concrete	Structural damage due to overloads?	□	□
	Corrosion of steel reinforcement?	□	□
	Check concrete for cracking, spalling, and exposed rebar	□	□
Foundation Block: Steel	Evaluate the loss of steel due to corrosion	□	□
	Look for cracks in welds	□	□
	Deformed structure	□	□
Blocks: General	Soft caps minimum thickness 2 in. and no crush prior to docking	□	□
	Spacing and location as per blocking arrangement (±0.5 in. transversely, ±1 in. longitudinally, ±0.25 in. height)	□	□
Keel Blocks	Sight keel block line for alignment and fit	□	□
	Keel block height meets requirement	□	□
	Keel profile applied to keel block offsets	□	□
Bilge Blocks	Sight bilge block line for alignment and fit	□	□
	Bilge block construction is within required dimensions	□	□
	Bilge block construction (force normal to vessel's hull passes through middle one-third of all blocks, no gaps, cribbing if over 6 ft.)	□	□
Miscellaneous	Crane clearance	□	□
	Check overhead interferences and clearances	□	□
	Depth of water (tide-dependent)	□	□
	Condition of the working floor for debris, unevenness, etc.	□	□
	Check mooring system	□	□
	Note draft/trim devices in use	□	□
	Condition of fendering	□	□
	Condition of lifting straps	□	□

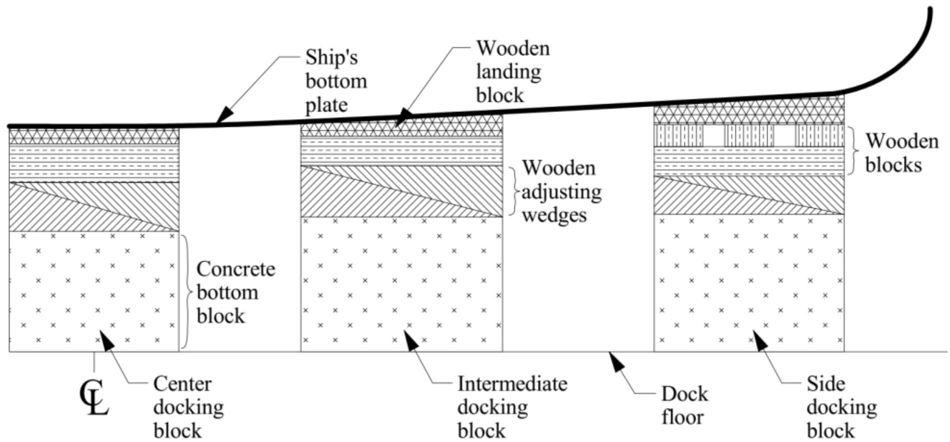

Figure 3. Example of a docking block arrangement (adapted from (House, 2016).

After the maintenance and repair activities in the dock are completed, the process of refloating the ship begins. At this stage, the balance of the ship, which is safely resting on the docking blocks, must be carefully checked, and the dock should be refilled with water gradually. Introducing water in a controlled manner ensures that the ship floats evenly and separates safely from the docking blocks. Once sufficient buoyancy is achieved, the ship is slowly and carefully moved out of the dock. This process is critical for the safety of both the ship and the dock and requires constant supervision and coordination throughout the operation. The procedures for exiting the ship from the floating dock should be systematically checked using a document similar to the audit list presented as an example in Table 4.

Floating docks bring a unique set of challenges compared to fixed docks, the most important being stability. While serious incidents are rare, when they do occur the consequences can be significant. Experience shows that many of these problems trace back to the ballast water system, which is responsible for keeping the dock balanced. If one part of this system fails, the dock can quickly become unstable, creating the risk of capsizing or even sinking (Conde, 2023).

Table 3. Typical repair and maintenance activities carried out during dry docking operations (House, 2016).

Work Item	Description
Ship's bottom cleaning	Cleaning the underwater hull using high-pressure water or grit blasting.
Hull painting	Painting and recoating the underwater area and boot topping of the hull.
Chain locker maintenance	Cleaning and painting the chain locker.
Anchor and cable inspection	Ranging and inspecting the anchors and cables.
Stuffing box maintenance	Inspecting and re-packing all underwater stuffing boxes.
Valve overhaul	Overhauling all underwater valves.
Stabiliser inspection	Inspecting stabilisers (fins) for corrosion and operational quality.
Sacrificial anode renewal	Renewing sacrificial anodes as and where appropriate.
Rudder and propeller survey	Examining rudder and propeller arrangement (including survey requirements of the tail end shaft).
Sea water intake cleaning	Cleaning all sea water intakes and straining arrangements.
Markings maintenance	Inspecting and painting draught marks, Plimsoll line, and freeboard markings.
Propeller polishing	Cleaning and polishing propeller(s).
Clearance check	Checking clearances around propeller and rudder fittings.
Tank plug maintenance	Drawing tank plugs relevant to tank draining schedule.
Fresh water tank cleaning	Cleaning freshwater tanks as appropriate.
Bow thruster inspection	Inspecting bow thrust units for corrosion or damage and implementing corrective action if required.
Windlass maintenance	Inspecting windlass and renewing brake linings, if required.
Pipe and gasket renewal	Renewing pipe lagging and flange gaskets as required.
Steel work repairs	Conducting general steel work repairs, e.g., flame cutting or welding.

Table 4. Example checklist for the undocking operation (Harren, 2010).

Item	Satisfactory	Unsatisfactory
Communication check	□	□
All equipment retracted	□	□
Verify temporary services/disconnection	□	□
Personnel at hull openings	□	□
Stopped at correct draft for hauling side blocks	□	□
Hauled all side blocks fully	□	□
Detection of any leaks	□	□
Vessel exited smoothly. Could it have hit any underwater obstacles?	□	□
Damage (describe)	□	□
Time and Date Vessel Is Completely Clear of the Sill ……….. , ………		
Drafts: FWD ……….. , MID ……….. , AFT ………..		

5. Conclusion

Floating docks play a central role in modern ship repair and maintenance by offering mobility, adaptability, and shorter turnaround times compared to traditional graving docks. However, their successful utilization depends on careful investment planning, proper integration with shipyard infrastructure, and strict adherence to operational standards. As demonstrated in past incidents, even relatively minor technical malfunctions in ballast or valve systems can escalate into severe accidents, highlighting the need for vigilant monitoring and robust risk management practices. For shipyards, floating dock investments should be approached not only as an expansion of capacity but also as a long-term strategic decision shaped by market demand, environmental regulations, and cost considerations. Future developments are expected to focus on environmentally friendly technologies, faster and more cost-effective maintenance, and the use of digitalization and automation to enable smarter monitoring and safer dock operations.

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CHAPTER 6

REDEFINING MARITIME AUTHORITY: LEGAL AND LIABILITY CHALLENGES IN THE AGE OF AUTONOMOUS SHIPS

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Abstract

The advent of Maritime Autonomous Surface Ships (MASS) marks a transformative juncture in global maritime transport, driven by rapid advancements in automation, artificial intelligence (AI), and digital connectivity. While autonomous vessels promise safer, more efficient, and environmentally sustainable operations, they simultaneously disrupt the foundations of traditional maritime law, which has long centered on the authority and accountability of the ship's master. As decision-making shifts to remote control centers and AI-based systems, conventional notions of command, liability, and jurisdiction require fundamental reinterpretation. Key challenges include the applicability of existing conventions (SOLAS, COLREGs, MARPOL, and UNCLOS), certification and insurance frameworks, cybersecurity governance, and the attribution of fault within complex human–machine ecosystems. Emerging national models, such as Norway's YARA Birkeland and Japan's MEGURI2040, offer valuable precedents yet underscore the absence of global harmonization. The forthcoming IMO MASS Code, expected to enter into force in 2032, constitutes a critical step toward normative integration but leaves essential gaps in liability distribution and enforcement mechanisms. This study argues that achieving legal coherence for autonomous shipping requires a paradigm shift toward shared responsibility models, adaptive regulatory design, and proactive international coordination to ensure that technological innovation evolves within a secure and accountable legal architecture.

Keywords: Maritime autonomous surface ships (MASS), Liability and regulation, International maritime law.

1. Introduction

The maritime industry has undergone a significant transformation in recent years driven by rapid technological progress such as digitalization, artificial intelligence (AI), automation, and data analytics. Among the most profound developments is the emergence of autonomous ships—vessels that may operate under remote supervision or in a fully autonomous mode. These ships are equipped with advanced sensors, perception, decision-making, and control systems that enable varying degrees of autonomy and human oversight(Abudu & Bridgelall, 2024). The International Maritime Organization (IMO) defines autonomous ships as Maritime Autonomous Surface Ships (MASS), which are "ships whose essential operational functions can be performed without human intervention"(IMO, 2018).

Autonomous ships promise significant potential for maritime transport in terms of safety, efficiency, cost optimization, and environmental sustainability. Key anticipated benefits include a reduction in human-error-induced accidents, lower operational expenditures, and optimized energy utilization(Kurt & Aymelek, 2022). However, the integration of autonomous systems into the maritime sector presents substantial uncertainties regarding existing legal regulations, safety standards, and international cooperation(Kim et al., 2020; Komianos, 2018). In light of these gains and concerns, the IMO aims to integrate a regulatory framework for MASS that aligns with contemporary and emerging technological realities (IMO, 2021a).

Current maritime law is primarily shaped around the traditional construct of the ship's master, who remains the ultimate authority and legal representative of the vessel. The master is responsible for many critical matters, including navigational safety, vessel management, cargo integrity, crew welfare, and environmental compliance under both national and international legislation. With the introduction of autonomous ships, the question of how to redefine the master's role, authority, and responsibilities has emerged as a central legal and ethical dilemma. Especially in the case of fully unmanned vessels, it is not yet clear to whom—or to which system—the existing "command" authority should be attributed. Therefore, the IMO Maritime Safety Committee (MSC) has emphasized the importance of clarifying the legal meanings of "master," "crew," and "person in charge" when designing the MASS regulatory framework(IMO, 2023).

Furthermore, the operation of autonomous ships presents a series of interrelated legal, technical, and ethical challenges, including flag, port, and coastal state jurisdiction; vessel certification and insurance mechanisms; search and rescue (SAR) obligations; cybersecurity vulnerabilities; and the allocation of liability in the event of accidents. In this context, the need to establish an internationally harmonized legal framework among regulatory authorities, industry stakeholders, and technology developers is becoming increasingly urgent. Accordingly, under the 2024 IMO roadmap, the mandatory MASS Code is scheduled to enter into force on January 1, 2032, marking a pivotal step toward regulatory integration(IMO, 2021a).

This chapter examines the legal aspects of autonomous ships from a multifaceted perspective. First, it explores the evolution of the ship master's legal authority within autonomous operational contexts. Next, it analyzes the legal implications of unmanned ship operations, focusing on regulatory challenges and global case studies. Finally, it proposes forward-looking recommendations addressing maritime rights, risk distribution, and liability regimes applicable to autonomous navigation.

2. Autonomous Ships and the Legal Authority of the Master

For centuries, maritime law has recognized the master as the ultimate authority and responsible person for the ship. This authority and responsibility are secured by regulations in both national and international law. The fundamental conventions of the IMO, particularly the International Convention for the Safety of Life at Sea (SOLAS), Convention on the International Regulations for Preventing Collisions at Sea (COLREGs), and International Convention for the Prevention of Pollution from Ships (MARPOL), define the master's duties and authorities in detail (COLREG, 1972; MARPOL, 1973; SOLAS, 1974). Table 1 summarizes the duties and authority of the master, both legally and operationally, within the framework of SOLAS, COLREGs and MARPOL.

Table 1. The Duties and Authority of the Master

Convention	**Focus Area**	**Essential Duties and Authority of the Master**
SOLAS	Life safety and safe operation	Safe navigation with full authority, drills, emergency management, accident reports
COLREGs	Collision prevention	Right of way, maneuvering, lookout, speed control, special circumstances measures
MARPOL	Environmental protection	Pollution prevention, record keeping, discharge regulations, environmental training

2.1 The evolution of the master's traditional role

From the earliest periods of maritime history, the master has held a central position in ensuring the safety of ship navigation, crew discipline, and the successful completion of the voyage. From ancient times to the modern era, the role of the master has included functions beyond being just a ship manager, but also a leader, law enforcer, and crisis manager (Morgan, 1953).

The authority of the master in traditional shipping included not only technical decisions to be taken for safe navigation but also the duties of resolving disputes and maintaining discipline among the crew. Especially during the sailing era, during long and dangerous sea voyages, the master ensured the voyage's success through his navigational knowledge, and it also served as a social equilibrium by maintaining order on board (Dickinson, 2008).

From the 19th century onwards, the traditional role of the master was transformed by the emergence of steamships and the impact of the industrial revolution. While technological advances offered new tools to support decision-making processes, the master's ultimate authority remained unchanged. However, masters are increasingly associated with legal and commercial responsibilities. For example, the development of international maritime law and the widespread adoption of maritime insurance practices have transformed the master from a figure solely responsible for navigation to a commercial representative (Stopford, 2008).

From the second half of the 20th century onward, with the entry into force of international maritime conventions (e.g., SOLAS, MARPOL, COLREGs), the master's duties and responsibilities were institutionalized and standardized. In this context, the master's role can be defined not only as a leader with authority over the ship but also as a safety and environmental protection agent who ensures compliance with international regulations (IMO, 2020)

Today, mastership is undergoing a new evolution with the development of digitalization and autonomous ship technologies. The modern master operates in an environment equipped with advanced navigation technologies, automation systems, and remote support tools. However, the proliferation of AI-powered decision-making mechanisms is transforming the master's traditional authority, bringing their role closer to that of a "bridge between technological systems and the human factor" (Burmeister et al., 2014).

In summary, as Table 2 illustrates, the role of the master has evolved throughout history to encompass technical, legal, commercial, and social dimensions. While maritime knowledge and leadership skills were at the forefront in the traditional era, today's master role has become a multifaceted professional field intertwined with technological literacy, knowledge of international law, and environmental sustainability principles.

Table 2. The Traditional and Modern Role of the Master: A Comparative Analysis.

Content	Traditional Role (18th–19th centuries)	Modern Role (20th–21st centuries)
Authority and Leadership	Absolute authority: decisions are implemented without debate.	Increased sharing of authority; coordination with crew, company management and remote monitoring centers.
Navigation and Technical Information	Direction finding using manual methods such as stars, compass and logbook.	Advanced navigation with GPS, ECDIS, radar, AIS and AI-based decision support systems.

Legal Liability	Responsibility based on traditional maritime practices.	Liability based on standardized and written law within the framework of international agreements (SOLAS, MARPOL, COLREGs).
Commercial Function	Conducting commercial relations as the shipowner representative of the ship	Commercial functions are largely transferred to the shipowner company and shore offices, with the master focusing on operational responsibilities.
Crew Management	Discipline and hierarchy are at the forefront; authority is reinforced through punishment.	Leadership, communication and human resources management approach; occupational health and safety norms are at the forefront.
Environmental Responsibility	Environmental protection is secondary; the primary concern is the safety of ship and cargo.	Environmental protection through MARPOL and climate-focused regulations is among the master's primary responsibilities.
Technology Adaptation	The human factor and experience are decisive.	Intensive interaction with automation, sensors, remote operation centers and AI-supported systems.
Crisis Management	Individual decision making based on sailor's intuition and experience.	A collective process managed with technologically supported risk analysis, crisis scenarios and international protocols.

2.2 The impact of autonomous systems

The historical evolution of the master's profession has been shaped in parallel with technological advances. The latest stage of this evolution is comprised of autonomous systems, known in maritime circles as MASS. Autonomous ships are technological structures that require varying levels of human intervention and have the potential to fundamentally change the way maritime operations are managed. The IMO has classified these systems into four levels based on their degree of operational independence(IMO, 2018, 2021c).

Level 1: The ship is equipped with automation systems, and a human crew constantly monitors the operation.
Level 2: Remotely controlled ships operate with a limited number of crew members on board.
Level 3: Remotely controlled, fully unmanned ships.

Level 4: Fully autonomous ships perform all operations without human intervention.

Increasing autonomy across these levels gradually diminishes the physical presence and direct control of the ship's master. While traditionally the master was defined as the ultimate authority over the ship, autonomous systems are reshaping the spatial and functional boundaries of this authority. At Level 3 and Level 4 autonomy levels, in particular, the master's function is assumed by operators in remote control centers. This fundamentally transforms the classic "mastership" relationship and represents a transfer of responsibility to a "virtual" authority(Liu et al., 2022).

Ultimately, the rise of autonomous systems is transforming the master's profession from one centered on physical authority to one based on digital accountability. This transformation is not merely a technical innovation; it is also a structural shift that requires redefining maritime law, human factors management, and professional ethics.

2.3 Transformation of legal powers and responsibilities

The legal position of the master on autonomous ships presents a new paradigm that challenges traditional maritime norms. Existing international regulations (e.g., SOLAS, MARPOL, United Nations Convention on the Law of the Sea - UNCLOS, and Standards of Training Certification and Watchkeeping - STCW) require the master to be physically present on board and assume ultimate responsibility for navigation, safety, and environmental protection. However, in autonomous systems, this model evolves in three fundamental ways.

- ***Change in Physical Command Location:*** The master no longer operates on the ship but from a land-based control center. Commands issued via satellite communication systems and data links blur the spatial boundaries of de facto authority. This creates legal uncertainties, particularly in maritime accidents, in processes such as jurisdiction, evidence collection, and crime scene determination(Ringbom, 2019).
- ***Sharing the Decision-Making Process:*** AI-powered autonomous systems can independently make decisions such as route determination, speed optimization, and collision avoidance. This raises the questions of "who is the decision maker?" and "who is responsible?" The master's role is evolving from a direct decision-making authority to a "control mechanism" that monitors the system's (Burmeister et al., 2014).
- ***Distribution of Legal Liability:*** Autonomous ships operate within a complex technical ecosystem. Therefore, in the event of a malfunction or accident, responsibility does not fall solely on the master; a multi-layered

responsibility structure is created, shared among system manufacturers, software developers, data providers, and remote operators. This transforms the classic "chain of command" concept into a technical "system chain".

Therefore, the proliferation of autonomous systems necessitates a redefinition of the master's legal status. Questions such as "Who is the master?" and "Who has the authority?" have become fundamental debates in the autonomous maritime era.

2.4 The human factor and the ethical dimension

The rapid advancement of technology does not mean that the human element in maritime operations will be eliminated. On the contrary, autonomous systems are shifting the human role from physical operation to cognitive control and ethical decision-making. Masters and operators in remote operations centers will be directing maritime traffic from hundreds of kilometers away, but the consequences of their decisions will still impact real human lives (Porathe, 2021).

In this context, two fundamental ethical debates stand out. The first is the ethics of responsibility: When AI systems make mistakes, who will be held accountable? The second is the question of human reliability: When a human acts as the final controller of a system, can they maintain their attention and decision-making capacity under prolonged passive surveillance? These questions shape the ethical dimension of human-machine interaction in maritime operations and suggest that the master profile of the future will be defined by psychological, cognitive, and ethical competencies.

3 Legal Issues Regarding the Operation of Unmanned Autonomous Ships

Unmanned autonomous vessels are a symbol of a radical transformation in maritime transport, representing a structure that challenges the boundaries of existing national and international legal regulations. Crewless operations are not only a technological innovation but also a paradigm shift that requires a reinterpretation of the concepts of maritime authority, legal liability, and sovereignty (Islam, 2025). Because the current international maritime legal system relies heavily on human presence and the master's physical command of the ship, unmanned autonomous vessels necessitate a redefinition of this structure. In this context, the legal issues that may arise from the operation of unmanned autonomous ships can be addressed along four fundamental axes: jurisdiction (flag, port, and coastal state relations), certification and insurance processes, liability and compensation regimes, search and rescue obligations, and emergency management.

3.1 Flag state, port state, and coastal state authority

The tripartite sovereignty structure on which international maritime law is based—flag State, port State, and coastal State—governs the chain of authority and responsibility on conventional ships(UNCLOS, 1982). However, unmanned autonomous ships seriously challenge this structure.

- ***Flag State Authority:*** The flag state, which determines a ship's legal identity and navigation authority, has jurisdiction over the ship's seaworthiness documents, safety certificates, and crew qualifications. However, the absence of human crews on autonomous ships invalidates the conceptual foundations on which these documents are based (Chen, 2024). For example, it is unclear how documents such as "competence of certificate" or "seaman's identity card" will apply to unmanned systems.
- ***Port State Authority:*** Port states have the authority to inspect foreign ships (Port State Control-PSC). Including autonomous ships within this scope of inspection should include not only technical compliance but also new parameters such as cybersecurity, data integrity, and the reliability of remote-control infrastructure(IMO, 2021c). However, port state inspectors' capacity to inspect these systems is currently limited. This creates information asymmetry among inspection authorities and leads to significant gaps in implementation.
- ***Coastal State Jurisdiction*:** A state's right to control its territorial waters and exclusive economic zone constitutes coastal state jurisdiction. Autonomous vessels create new risks for coastal states in terms of navigational safety and environmental security. Therefore, coastal states must develop new protocols for monitoring, identifying, data sharing, and emergency response to these vessels(Eronen, 2023). Because international standardization has not yet been achieved, implementation differences and jurisdictional conflicts are likely to occur among different states.

3.2 Certification, insurance, and legal liability regimes

- ***Certification Issues:*** Fundamental international conventions such as SOLAS, MARPOL, and STCW are based on human-centered operations. Ship certifications stipulated in these conventions are designed to accommodate crew availability and response capacity(IMO, 2020). However, the extent to which requirements such as firefighting, lifesaving, and safety equipment for autonomous ships will apply to unmanned systems is uncertain. Therefore, it is essential that existing certification systems be updated to include new criteria such as the reliability of AI algorithms, sensor integrity, and the security of remote-control systems.

- ***Insurance and Reinsurance:*** Autonomous ships require a risk management approach that goes beyond traditional insurance approaches. Factors such as algorithmic decision errors, cyberattacks, or software malfunctions, rather than human error, create new risk categories(Thompson & Davies, 2023). Insurance companies must develop new definitions for who should attribute these risks (operator, software developer, hardware manufacturer, or remote operator). Furthermore, the scope of existing P&I insurance must be expanded or policies specifically designed for autonomous operations.
- ***Legal Liability Regime:*** Liability for accidents occurring on autonomous ships is no longer limited to the master and shipowner. As AI systems, data providers, manufacturers, and control centers play a role in decision-making processes, a multi-layered chain of responsibility emerges (Dean & Clack, 2019). This necessitates a redefinition of the concepts of "command authority" and "fault liability" in international law. A binding international liability model has yet to be established by the IMO or other institutions.

3.3 Search and rescue obligations and emergency management

Maritime tradition and the SOLAS Convention stipulate that every ship has the obligation to assist those in need at sea(SOLAS, 1974). However, the absence of crew members on unmanned vessels makes it impossible to fulfill this obligation effectively. This creates not only a technical but also a moral and legal gap. International regulators must develop legal and technical regulations that will enable rescue operations to be conducted through remote control centers in such situations.

Similarly, in emergencies such as fire, cargo leakage, or machinery failure, predictive AI algorithms and autonomous emergency response systems will replace traditional crew reflexes. Because the reliability of these systems directly impacts human life and the environment, their pre-testing and certification should be done in a framework of international standards(Blindheim et al., 2020; Manzur Tirado et al., 2019).

As a result, the legal status of unmanned autonomous ships presents an area not anticipated by the current international maritime regime. The concept of "master" is being redefined in terms of both maritime safety and liability law, and authority, decision-making, and oversight mechanisms are shifting from humans to technology. Therefore, a coordinated effort between the IMO, IACS, and national maritime authorities to establish a new international regulatory architecture specific to autonomous ships is essential(IMO, 2019).

4 Regulation of Autonomous Ships: Concepts, Challenges, and Examples

Existing international maritime regulations—particularly SOLAS, MARPOL, STCW, and UNCLOS—are founded on human-centric operational assumptions. Therefore, the emergence of autonomous systems necessitates regulatory restructuring at both the conceptual and normative levels(Dean & Clack, 2019; Ringbom, 2019).

Discussions on the regulatory framework for autonomous maritime transport generally fall under three headings: (i) conceptual definition and classification issues, (ii) regulatory challenges, and (iii) experiences from previous implementation examples.

4.1 Conceptual definition and classification issues

For new technology to be legally regulated, its definition must first be clearly and functionally determined. However, this requirement has not yet been fully met in the context of autonomous ships. The proposed a four-level autonomy scale by IMO classified according to the extent to which the ship requires human intervention(IMO, 2021c). However, this definition focuses more on technical capacity, and uncertainties persist in areas such as legal status, authority allocation, and distribution of responsibilities.

Different conceptual frameworks are also used at the national level. Norway defines autonomous ships as "marine vessels that can make decisions and navigate without human intervention," while countries such as China and Japan assess their level of autonomy based on technical control parameters(Abdelhady, 2024; Li & Fung, 2019). This definitional diversity makes both international standardization and legal harmonization difficult.

4.2 Regulatory challenges

The main legal and institutional challenges faced in the regulation of autonomous ships can be categorized into three main groups:

4.2.1 Regulatory incompatibility and normative gaps

International maritime conventions assume that operations are conducted under human presence. Roles such as "master," "navigating officer," or "seafarer" form the basis of existing regulations. Autonomous ships either eliminate or transform these roles. Therefore, direct application of conventions such as SOLAS, STCW, or MARPOL is not possible(Ringbom et al., 2021). The solution appears to be to revise these conventions or establish a parallel regulatory framework for autonomous systems.

4.2.2 Cybersecurity and data sharing

Autonomous ships are heavily dependent on sensor networks, software systems, and remote communication infrastructures. However, binding provisions regarding cybersecurity, data integrity, and AI decision-making processes are limited in current maritime legislation(IACS, 2021). A potential cyberattack could impact not only ship security but also environmental risks and maritime traffic. Therefore, defining data security and cyber defense mechanisms at the international level is a priority.

4.2.3 Jurisdiction and dispute resolution

The separation of control from physical location in autonomous systems creates new uncertainties regarding jurisdiction. For example, if a Norwegian-flagged ship is managed remotely by an operator in India and the software infrastructure is operated by a US-based provider, the jurisdiction of which country's court will be debatable in the event of a maritime accident(Coito, 2021; Dong et al., 2024; Issa et al., 2022). This complicates both evidence collection processes and the determination of liability.

4.3 Previous examples and experiences

In the maritime sector, some countries have played a leading role in the development and testing of autonomous ships. These examples contribute to the development of regulatory frameworks and provide benchmarking opportunities for international policy design.

The YARA Birkeland project is the world's first fully electric and autonomous container ship. The Norwegian Maritime Administration (NMA) and the Coastal Authority developed special permits and regulations for trial operations of this project. This has created an innovative regulatory cooperation model between public authorities and the private sector (Kongsberg, 2017; Midtbo, 2021). Japan's MEGURI2040 initiative aims to expand MASS applications by 2040 (Suzuki, 2021). The program tests safety, energy efficiency, and environmental compliance criteria through pilot voyages.

On the other hand, the Suez and Panama Canal authorities do not yet allow fully autonomous vessel passage. This stance is based on high security requirements and sensitivity to national sovereignty. Therefore, the integration of autonomous systems is closely linked to national security policies.

The regulation of autonomous ships is still a developing field and has not yet reached normative maturity. Achieving conceptual clarity, harmonizing technical standards, and developing transboundary cooperation mechanisms are critical to its success. While IMO's MASS Regulatory Scoping Exercise is an important initiative in this area, it has not yet translated into binding legal norms(IMO, 2021b). Therefore, the future evolution of maritime law should be built on multilateral coordination, flexible regulatory principles, and the sharing of practical experience.

5 The Liability Regime in Autonomous Ships

With the proliferation of autonomous ships in maritime transport, the need to restructure the liability regime has given rise to one of the most complex debates in maritime law. Because current international maritime law is built on a human-centered structure, the distribution of responsibility is defined by a classical hierarchy centered around the master, owner, and flag state(Ringbom, 2019). However, the introduction of autonomous systems has introduced new actors in decision-making processes, such as AI algorithms, remote operation centers, software developers, and system integrators. This situation necessitates both the expansion and redefinition of the legal liability chain(Dean & Clack, 2019; Ringbom et al., 2021).

Table 3 demonstrates that the concept of maritime liability has evolved from a human-centered, hierarchical structure to a multi-actor, technology-based one. While the classical system features a clear distribution of responsibility among the master, owner, and flag state, it argues that in autonomous vessels, decision-making and implementation processes should be shared among algorithms, remote control centers, and hardware systems. This situation brings forward the concept of "distributed liability" rather than "single liability" and necessitates a redefinition of the fundamental concepts of existing international maritime law.

Table 3. Comparison of Liability Regimes for Classical Shipping and Autonomous Ships.

Area of Responsibility / Actor	Role and Responsibility in the Context of Classical Maritime Law	Changes / New Situation in Autonomous Ship Operations	Area of Legal Uncertainty or Controversy
Master	Personally responsible for the safe navigation of the ship, the management of the crew, and the consequences of the decisions made.	If they are not physically present on the ship, "command authority" is transferred to a remote operator or algorithm.	The concept of command needs to be redefined, and whether the status of master can be transferred to the virtual environment is debatable.
Shipowner	The shipowner is indirectly liable for the actions of the master and crew; compensation is payable in the event of maritime accidents.	The scope of liability expands in cases such as system failures, software errors, or cyberattacks.	It is unclear to what extent the shipowner will be held liable for system errors beyond technical control.
Flag State	It oversees the operation of the ship in accordance with international obligations and is responsible for oversight of safety of navigation and environmental protection.	New technical standards and remote monitoring mechanisms are required for the control of autonomous systems.	It is unclear how the flag state's control authority will be applied to remote operations.
Remote Control Centre (RCC)	It has no equivalent in the classical system.	It makes the ship's navigation and maneuvering decisions and has remote intervention authority.	It is unclear whether RCC personnel are considered to have the status of "master" or "operations officer."
AI Software Developers	Do not participate in the classical system.	They develop and update decision support algorithms and indirectly influence the decision chain.	It is unclear how damage arising from software errors relate to the classical concepts of fault or negligence(Guerra, 2017; Trivedi, 2023).
System Integrators and Hardware Manufacturers	Under the traditional system, they are solely responsible for maintenance and production.	They are indirectly liable for failures in technological infrastructure such as radar, sensors, and control systems.	The extent to which product liability principles can be applied to maritime law is debatable.

5.1 Liability, insurance, and the regulatory framework in autonomous ship operations

The structure of liability in autonomous shipping has become an area where different legal approaches intersect. In terms of liability types, three main categories stand out. The first is fault-based liability, which in classical maritime law encompasses liabilities arising from the master's negligence or the owner's lack of oversight. However, the unpredictable behavior of AI-based algorithms in autonomous ships limits the applicability of the traditional concept of fault and necessitates the development of new legal approaches(Ringbom, 2019). Second, strict or objective liability regimes are systems that hold those engaged in dangerous activities accountable without any requirement for fault; the adaptation of this approach for high-tech autonomous operations is increasingly being discussed. The third type is product liability, which refers to the liability imposed on the manufacturer or developer for damages arising from software or hardware malfunctions. In this context, it is still unclear how these responsibilities will be linked to maritime transport-specific contracts (e.g., carriage or charter party).

Insurance and compensation mechanisms will also need to be reconsidered due to the changing liabilities that will arise with the proliferation of autonomous ships. International marine insurance markets, particularly P&I clubs, have traditionally covered risks related to human error; however, it remains unclear whether risks arising from AI errors, data failures, or the intervention of remote operators will be included in the insurance coverage. While the feasibility of crew liability insurance on uncrewed ships and the coverage of remote operators' liability was addressed in specific studies(IMA, 2025), a uniform international practice still does not exist.

The current international regulatory framework also does not cover autonomous systems, creating a significant legal gap. Fundamental conventions such as MARPOL, SOLAS, STCW, COLREG and UNCLOS do not contain direct provisions for autonomous ships(IMO, 2021b) . The MASS Code aims to establish a binding regulatory framework; however, the process's inability to keep pace with technical development in the sector is causing regulatory delays(Fenton & Chapsos, 2023). Meanwhile, some states, such as Norway, Singapore, and Japan, have developed regulations for autonomous maritime transport within their national legislation; however, these regulations have limited validity in international disputes, raising issues of forum shopping and conflicting jurisdiction.

6 Conclusion

While smart and autonomous ships offer significant opportunities for efficiency and safety in maritime transportation, they also introduce a new paradigm in maritime law that pushes the boundaries of existing rules. This paradigm shift necessitates responding to technology not only through adaptation but also through a proactive regulatory and restructuring process. This transformation is not only a technical development but also a multidimensional evolution requiring a redefinition of legal and economic responsibilities. Otherwise, legal uncertainties will not only slow the sector's development but also pave the way for liability crises and international disputes.

The legal approach to autonomous ships is not fully compatible with classical maritime law principles. This highlights the need for reform of existing regulations. Stronger coordination between international maritime organizations and states, clarity regarding the responsibilities of new actors, and the development of comprehensive insurance systems will be key building blocks of this process. Otherwise, the resulting legal gaps will create both commercial uncertainty and pose serious risks to maritime security.

In the context of international maritime law, a ship is defined as a vessel registered by its flag state and used for maritime transportation. However, whether smart ships are fully autonomous or remotely controlled does not directly fall within this definition. In particular, the following questions remain unclear.

- Is a smart ship considered a "legally ship" without a crew?
- Can decisions made by AI be considered the same as those of the ship's master?
- Should a smart ship be considered an independent legal subject?

These questions suggest that the definition of a ship, as a subject of maritime law, needs to be reconsidered. Some legal scholars advocate granting smart ships limited legal personality. This would allow the ship to enter into contracts, recover damages, and be sued in its own name. However, this approach goes far beyond existing national and international legislation and has not yet gained general acceptance. In this context, it is critical that rights, obligations, and responsibilities be clearly defined, allocated reasonably among the parties, and regulated in international harmony. Otherwise, the proliferation of autonomous and intelligent systems will occur in a legal environment full of uncertainty and will increase risks in terms of both security and investment in the maritime sector.

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CHAPTER 7

THE CONTRIBUTION OF SIMULATION AND AUTOMATION-SUPPORTED MANUFACTURING TO SUSTAINABILITY IN SHIP BLOCK PRODUCTION

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Abstract

With the growing international commercial activities in the world, the scope of maritime transportation has expanded and the need for ships has increased. Shipyards can only meet this demand through a sound management system. Ships are marine vehicles that are produced at very high costs and require complex production processes and systematic engineering approaches. In this competitive environment, shipyards need to program their production processes and project management steps accurately and effectively. The future survival of manufacturing companies is directly proportional to their ability to carry production activities forward. Block production is the first of these production activities in the shipyard. Mounting, welding and grinding activities are carried out during the manufacturing process of the blocks that form the steel hull of the ship. Mounting and welding operations require electrodes, while grinding operations require the use of abrasive grinding wheels. The use of electricity is essential for these three activities. In production, errors in workmanship or design can result in defective work, necessitating reprocessing or rework. This can result in additional electricity consumption. Thus, more greenhouse gas emissions than necessary are generated during the block's production. This also results in a loss of labour. Reducing fault rates in production and increasing production amount can be achieved by improving the system and its applications. It is possible to prevent some faults in simulation and automation-supported production. Simulation models created using real data from a production line allow for process observation, allowing for proactive intervention to identify potential faults. Additionally, the use of automated mounting and welding machines, particularly on the panel line, during block manufacturing can help prevent individual faults. This reduces electrode, grinding wheel, and electricity consumption, thus preventing extra greenhouse gas emissions.

Keywords: Block production, simulation, automation, sustainability.

1. Introduction

On a global scale, approximately 90% of trade is carried out by maritime transport. This explains the significant share of the maritime industry among many other industries worldwide. Ships constitute the most important element of maritime transport. Thus, in this competitive environment, shipyards where ships are produced must use a management system where production processes are optimized, project steps are clearly planned, and process control mechanisms are followed. Because the project management steps in shipbuilding are well managed, and the project can be completed in accordance with the contract conditions, which can be a reason for shipowners who want to order ships to choose a shipyard (Hwang et al., 2014; Kafalı and Özkök, 2015). Otherwise, delays in ship deliveries will lead to high-cost overruns. (Kim et al., 2005; Jebbor et al., 2023). Capturing a sufficient share of the shipbuilding market and competing with countries like China, Japan, and South Korea can only be achieved through proper planning and good management. Furthermore, the shipbuilding industry is a global sector, and maintaining competitiveness in this field requires a production planning system capable of continuous improvement and on-time completion. (Frankel, 1985; Lee et al., 2018). The construction process of ships is not as highly automated as that of automobiles and airplanes. Even if the same type of ship is desired to be produced, production processes may differ depending on the shipowner's wishes. (Roh and Lee, 2007). In addition, although it is considered that planning in ship construction depends on the experience of the relevant personnel, efforts to establish an efficient production system are ongoing. (Lujibenkov et al., 2022).

The shipbuilding industry is a large and complex industry that consumes energy, materials, and human resources intensively; includes production and sub-industry activities; and also produces greenhouse gas emissions and waste on land and at sea (Helvacıoğlu and Helvacıoğlu, 2024). The construction of ships, which has a labour-intensive manufacturing process, is kept under supervision and control from the design stage. The blocks that form the basic building structure of the ship and are of critical importance in production require a consistent and systematic manufacturing process. (Dong et al., 2009). Blocks are structures formed by completing the mounting, welding and grinding processes of parts obtained from sheets cut in accordance with manufacturing drawings on CNC machines in a certain order. (Hur et al., 2015; Li et al., 2019). Mounting and welding operations utilize electrodes, while grinding is performed with abrasive wheels. All three uses require the usage of electricity. Consequently, greenhouse gas emissions due to the use of electricity and electrodes during the manufacturing of the blocks that form the ship are inevitable. Additionally, disruptions or design innovations may arise during production. In such cases, the completed work might require repairs or replacements. This case causes loss of labor and increased greenhouse gas emissions. As in every branch of industry, shipbuilding requires high-quality production with a low fault rate and acceptable levels of greenhouse gas emissions. To achieve this, improvement efforts on systems and applications are remarkable. Technological improvements have enabled the advancement of simulation techniques based on mathematical models, and these have been used effectively in marine engineering fields.

(Abdel-latif et al., 2013). Simulation-based production processes allow for the anticipation of potential problems and the implementation of necessary corrective and preventive actions. Besides, the rate of human fault will decrease in automation-supported jobs, and the use of consumables and electricity will reduce. It is of great importance to maximize efficiency, reduce labour requirements, decrease production costs, and create a systematic production flow. (Scalia et al., 2019).

2. Block Production in Shipbuilding

During the block production process, the shipyard's production and design departments work together. Firstly, the profiles and plates to be used in manufacturing are transferred to the production area and shot-blasting and primer painting processes are carried out. Based on information from the design department, plates are cut on CNC machines, and the necessary markings are made. The process creates single parts. These single parts are used in the pre-production section, creating the block's matrix. Furthermore, plates and profiles are combined to produce large-scale panels. The production of blocks is carried out by bringing together large structures such as matrix and panels and small parts such as brackets.

The block production process consists of three stages. The first stage is mounting. Here, the parts to be mounted must be attached to each other using spot welding, in accordance with the drawings. This stage is also very important for the second stage, the welding process. After that, in the welding process, the mounted parts are welded using a suitable full welding method. Then in the third stage, grinding is performed on necessary welds and sharp edges. Figure 1 shows these 3 stages.

a b c

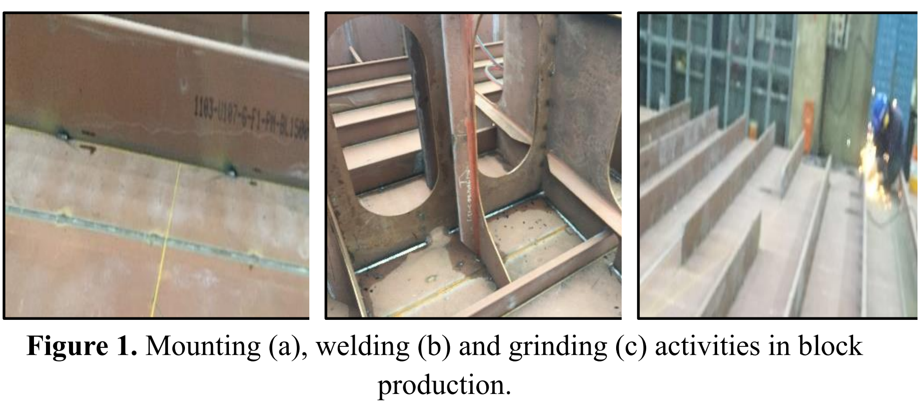

Figure 1. Mounting (a), welding (b) and grinding (c) activities in block production.

The block production process can be categorized under four main headings: preparation, pre-production, panel production, and block production. The material flow and sequence of production steps under these headings are shown in Figure 2.

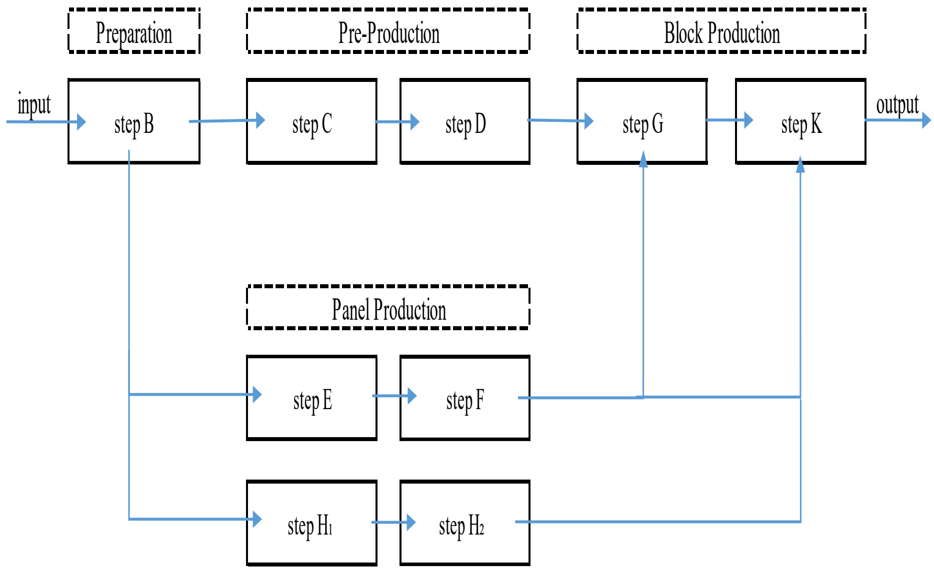

Figure 2. Block production and material workflow (Genç, 2024).

In step B, which is the preparation phase of the block production process, the plates are cut to obtain single parts. These parts are shipped to be used for step C in pre-production and for step E and step H_1 (bending) in panel production. Matrix structures are obtained in step D by using the interim products produced in step C. In step E, panels are produced, and in step F, profiled panels are obtained by welding the profiles. After that, in step G, matrix structures and profiled panels are combined. In step H_2, the welding of the bent panels is completed, and finally the block production is completed in step K. In all these implementations, mounting, welding, and grinding processes are carried out. This systematic approach ensures that each step of production is efficiently executed, resulting in high-quality components. Here, excluding step B, the interim products and block are shown in Figure 3 below.

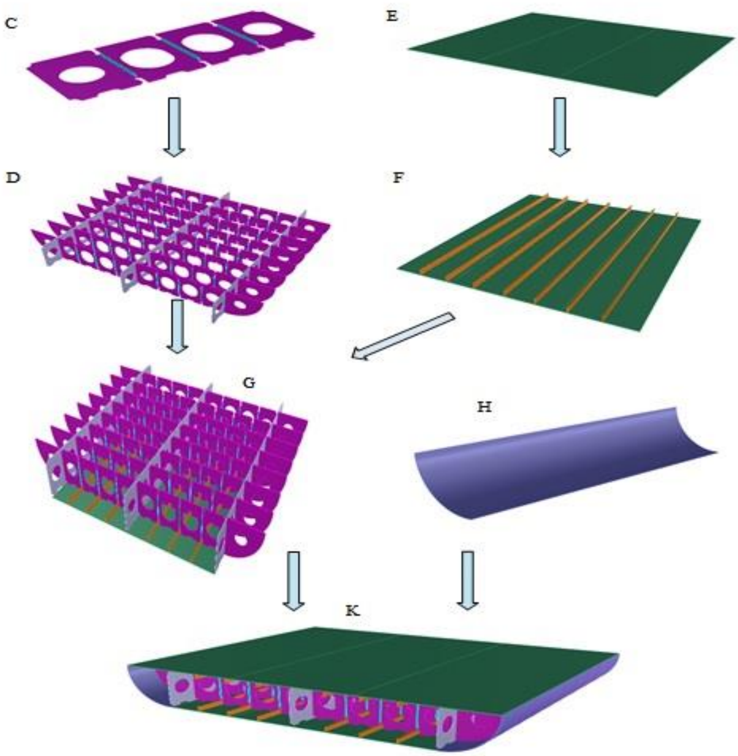

Figure 3. Interim products and block (Adapted from Kafalı, 2020).

3. Literature Review on Simulation and Automation-Supported Block Production

When examining the studies aimed at improving the manufacturing processes of the blocks, it is particularly noticeable that simulation techniques are used extensively. It is also observed that heuristic methods and mathematical models are incorporated into the production process, and improvement studies are performed, especially in the panel line. Thus, it is aimed at regulating labour and time management, eliminating losses, and reducing faults to minimum levels. This approach supports the reduction of greenhouse gas emissions by reducing electricity and electrode usage and reducing labour losses resulting from rework.

Cho et al. (1999) worked on an automatic welding plan for block manufacturing that included the position, material, method, and equipment of the weld. They used topological relationships between the parts of the block and their arrangement in the assembly. Roh and Lee (2007) obtained a simulation model of the entire block production process using 2D drawings. By applying this model in the field, they demonstrated that simulation can be created at the initial design stage of block assembly. Seo et al. (2007) developed a case-based reasoning system for process planning in block assembly. Here, they proposed two similarity coefficients to find similar cases and considered the visual similarity between parts in the block. They mentioned that the system could be made more efficient. In their study, Dong et al. (2009) proposed a stochastic method that allows flexibility in the production processes of flat and curved blocks, enabling curved blocks to be constructed in areas where flat blocks are also used. In practice, they demonstrated an improvement in average production performance using discrete event simulation. Cha et al. (2010) proposed an integrated simulation method for improving shipbuilding process planning. They observed that this simulation method could also assess potential negative interactions between blocks within the process, thereby reducing labour and time losses. They also applied this study to the block assembly process. Another study on blocks was performed by Hu et al. (2015). In this paper, they identified the block manufacturing area problem as a crucial bottleneck in the shipbuilding process. They developed a heuristic hybrid algorithm for the block manufacturing area and performed a simulation study for validation. Yang et al. (2016) considered the scheduling problem in panel block manufacturing as a multi-objective fuzzy flow scheduling problem. They incorporated fuzzy delivery date, fuzzy processing time, and on-time delivery concepts into this scheduling. They observed improvements in the process by using the multi-objective particle swarm optimisation they developed to solve the problem. Another study on the optimisation and scheduling of blocks in the panel line was presented by Wang et al. (2016). In the proposed model, a non-linear integer programming model was established for each sub-problem, taking into account numerous uncertain factors. The solution utilised rolling horizon and rescheduling applications. Furthermore, a penalty function aimed at reducing the costs incurred by early or late deliveries was presented. Urbanski et al. (2018) investigated the effect of parameters such as the number of elements specified on the panel line in block manufacturing, line length, material usage, and labour on the usability of the line. Accordingly, they identified areas that reduced the efficiency of the production line and suggested ways to modernise it. Li et al. (2019) proposed a three-stage method to determine the production and idle times required during block manufacturing. In the first stage, they clustered the blocks according to their characteristics using the K-Means algorithm. In the second stage, they used the data envelopment analysis (DEA) model to evaluate the planned production time. Finally, they trained an artificial neural network model to enable the reuse of this data. Genç et al. (2024) developed a two-stage stochastic mathematical model to determine the required labour force in block manufacturing. The sample average approximation approach was used to solve the proposed model, and the minimum workforce was obtained. Otero et al. (2024) proposed a statistical procedure that successfully predicts the placement of transverse pieces within longitudinal elements in block manufacturing. They also performed a simulation study to evaluate the performance of this statistical procedure. Kwak et al. (2025) suggested a two-stage model to optimise the flow on the block production line. By testing this model on two cases, they verified that production was completed in a shorter time compared to manual planning.

4. Contribution of Simulation and Automation to Sustainability

The United Nations Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report, published in 2022, states that the increase in human-induced greenhouse gas emissions poses irreversible risks to nature and humanity, such as destroying nature, damaging food production, and slowing economic growth. Furthermore, it emphasized that future efforts to address this situation must be undertaken at the international scale (IPCC, 2022). Accordingly, to prevent risks and protect the environment and nature, it is crucial to establish sustainability science as an academic discipline and to achieve a global awareness of sustainability by tackling challenges that existing disciplines do not address (Takeuchi, 2018). This is because sustainability is a global concept with various dimensions, such as social equality, culture, world peace, social justice, and welfare (Hariram et al., 2023). Thus, an interdisciplinary approach across many fields is necessary to develop a comprehensive understanding.

The concept of sustainability has become a common statement encountered in all areas of life. Particularly in the industrial sector, rapid developments, the careless use of resources, the increasing production, unconscious consumption, and the emergence of social problems such as poverty and hunger have made the concept of sustainability even more crucial. The focus of this study, sustainability in production, refers to the situation that aims to minimise the damage caused to the environment in production processes. Sustainable development involves three fundamental factors: the environment, the economy, and society, and these factors interact with each other (UN, 2025). This interrelationship is illustrated in Figure 4.

Production planning is a complex activity that enables manufacturing to proceed efficiently (Khaled et al., 2022) but requires proper coordination between departments (Alam, 2023). In traditional production planning, the focus is on reducing costs, increasing efficiency, and maximising production.

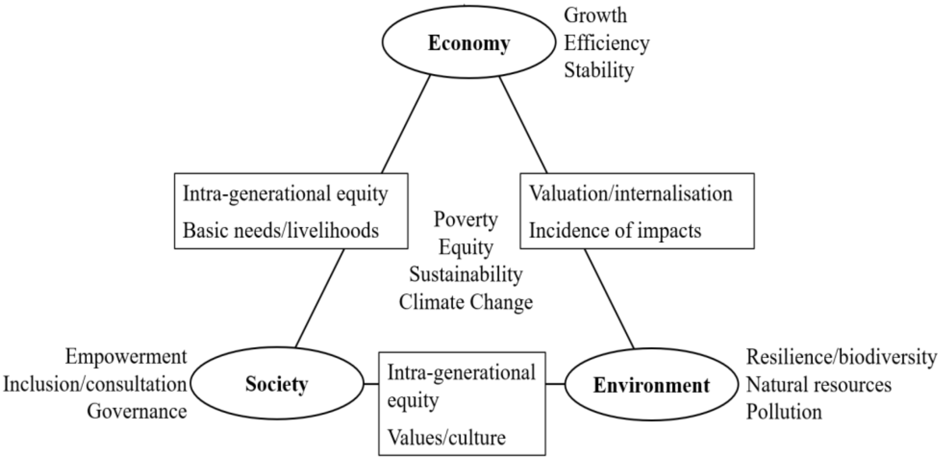

Figure 4. The three interconnected pillars of sustainable development: environment, economy, and society (Adapted from Munasinghe (2004)).

Thus, economic factors are prioritised over environmental and social factors (Jabbour et al., 2020; Saeed Khaled et al., 2024). In the study evaluating the effects of sustainability on production planning, it was emphasized that the environmental dimension contributes to reducing greenhouse gases, the economic dimension contributes to reducing costs, and the social dimension supports employment (Ortiz et al., 2025). Therefore, manufacturing companies must adopt the concept of sustainability, develop new strategies, consider the life cycle, reduce human faults in production through automation-focused work approaches, and manage processes with a focus on material and energy savings (Yavuz, 2014).

The management and production processes carried out in shipyards consist of multidimensional activities that require the simultaneous involvement of human resources, energy use, greenhouse gas emissions, and terrestrial and aquatic ecosystems. Hence, this sector encompasses all activities and requirements defined within the scope of sustainability, such as increasing energy efficiency, reducing greenhouse gas emissions, decreasing water consumption and waste production, and extending product life cycles (Helvacıoğlu and Helvacıoğlu, 2024). This multi-dimensional structure is directly related to the sector's sustainability goals; in this context, methods such as lean practices improve productivity and efficiency while supporting economic, environmental, and social sustainability (Neves et al., 2025).

Simulation and automation-supported manufacturing can make valuable contributions to sustainability in ship block production. These approaches can minimize labour costs and production delays by identifying potential bottlenecks and sources of faults in production processes, thereby reducing material and energy waste. This leads to cost savings while also increasing competitiveness. In environmental terms, optimising production processes can contribute to the conservation of natural resources by reducing energy consumption and greenhouse gas emissions, as well as decreasing the amount of waste due to material usage. Furthermore, the use of automation in hazardous and heavy work has a beneficial impact on occupational health and safety, while simulation can contribute to increasing the qualified workforce by enabling the development of engineering and digital skills. In this context, simulation and automation-supported manufacturing applications can contribute holistically to the economic, environmental and social dimensions of sustainability in ship block production.

5. Conclusions

As in many other industries, the shipbuilding sector must keep pace with the times and remain innovative. However, this progress must adopt environmentally friendly approaches and pave the way for contributing to sustainability. Although environmentally friendly approaches are challenging in industries that rely heavily on human labour, efforts are being made to encourage this process. This study addresses the manufacturing processes of blocks, which are an essential step in shipbuilding, and the work performed to improve these processes. Simulations and mathematical models employed in block production and erection have been found to contribute to supporting the overall process. Notably, they have yielded useful results particularly in terms of preventing time losses, reducing production duration, balancing the workforce, and preventing faulty production. This demonstrates that the idea that excess electricity consumption during production can be prevented and that potential defects can be detected early, allowing blocks to be manufactured using fewer electrodes.

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CHAPTER 8

APPLYING DIGITAL PRODUCT PASSPORTS IN THE MARITIME INDUSTRY: PERSPECTIVES ON CIRCULARITY, TRACEABILITY, AND SUSTAINABILITY

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Abstract

This section examines the impact of the Digital Product Passport (DPP) approach on circularity, traceability, and sustainability goals in the maritime industry, using relevant examples and literature. The DPP makes data about product/component identity, material composition, maintenance and repair history, life cycle assessment (LCA), environmental performance, and end-of-life scenarios all the same. This makes it easier for different stakeholders along the value chain to share data that is accurate.

The literature review shows that DPP implementations have measurable benefits, such as saving time and money on material-related tasks, making it easier to see material flows and inventories, making maintenance planning more accurate, raising recovery rates, and making the supply chain more open. However, there are still many problems that need to be solved. Data standardization and interoperability are still not in place, there are worries about data privacy and competitive sensitivity, and small and medium-sized businesses (SMEs) have trouble with infrastructure costs, hiring people, and digital skills. These problems show how important it is to have integrated governance, standardize technology, and build capacity in order to make DPP work well in the maritime industry.

Keywords: Digital Product Passport (DPP), Circular Economy, Sustainability, Lifecycle Management.

1. Introduction

The maritime industry has long lasting, expensive assets, complicated worldwide supply chains, and a lot of material and energy inputs. All of these require a lot of data to keep track of materials and operations. At this scale, problems with traceability and circularity can lead to inefficient maintenance cycles, difficulties in managing hazardous materials, and hidden costs during recycling and end-of-life operations. The Digital Product Passport (DPP) could help fix these problems by digitizing and standardizing key product information such as material composition, origin, maintenance and repair history, and end-of-life scenarios. This would make the product lifecycle more transparent and help stakeholders make better data driven decisions.

The Circular Economy Action Plan (European Comission, 2020) and the Ecodesign for Sustainable Products Regulation (Regulation EU, 2023) are the main institutional frameworks that support the DPP concept in the European Union. The Batteries Regulation (Regulation EU, 2024) represents the use case of DPPs, introducing the Digital Battery Passport. In the maritime industry, the

EU Ship Recycling Regulation (Regulation EU, 2013) mandates the Inventory of Hazardous Materials (IHM) to monitor and manage hazardous substances onboard vessels. Extending this framework with DPPs could enable traceability down to the component and material level, allowing for real-time end of life planning. Moreover, this integration would enhance compliance with international regulations such as the IMO and strengthen EU inspection frameworks.

Adisorn et al. conceptualized the DPP from a systems and stakeholder perspective, emphasizing the mapping of data domains to specific actor value contributions (Adisorn et al., 2021). Their framework shows that material, process, and lifecycle data can be systematically tied to producer, regulator, and recycler needs creating a value driven foundation for digital servitization in circular economies. Similarly, Jansen et al. highlighted that maritime production systems can benefit from this structure through improved asset information exchange and digital documentation, leading to stronger cross organizational collaboration and data integrity throughout shipbuilding and operation. European initiatives like CIRPASS and CIRPASS-2 build upon these foundations, developing harmonized standards, interoperable schemas, and sectoral pilots (CIRPASS; CIRPASS2). The CirclesOfLife project complements these efforts by designing Environmental Performance Indices (EPIs) for shipyards, effectively linking DPP data with green port and vessel operations (Circles of Life).

Maritime industries operate within highly complex, globalized systems that demand enormous quantities of materials, energy, and data coordination. Bhati et.al. (Bhati et al., 2025), shows that shipbuilding and fleet operation depend on long term assets whose digitalization remains uneven, leading to inefficiencies in data exchange and environmental monitoring. The resulting lack of standardized material traceability limits the ability to evaluate embodied carbon, repair cycles, and recycling potential issues that are increasingly central to sustainable maritime strategies. Scholars and practitioners have begun to position Digital Product Passports (DPPs) as a framework for connecting lifecycle information across production, operation, and end-of-life phases.

The conceptual foundation for DPPs is also defined in other works (Rosado da Cruz and Cruz, 2025) (Wicaksono et al., 2025). These studies describe the DPP as a structured digital repository that aggregates technical, environmental, and economic data on a product's journey from material sourcing through disposal or reuse. In maritime contexts, the passport can integrate component level specifications, maintenance histories, and environmental indicators within a unified data environment. The purpose is not only documentation but also real time accessibility of reliable data to shipyards, equipment suppliers, classification societies, and regulatory agencies.

DPPs can supply verified material and maintenance information to the digital twins, ship operators can optimize fuel use, extend component lifetimes, and plan decommissioning processes more accurately. This dynamic feedback loop is important to the transition from reactive maintenance toward predictive, sustainability driven lifecycle management.

Insights from (Koilo, 2025) reveal that digital servitization strategies where products are accompanied by data based services expand the role of DPPs beyond compliance tools into business model enablers. By embedding product passports in service contracts and monitoring systems, shipbuilders and suppliers can shift toward value creation through maintenance performance, reuse, and recycling efficiency rather than pure material throughput. This transition aligns with the study (Zhang and Seuring, 2024), which stresses that information transparency is a prerequisite for circular supply-chain design and risk reduction.

Further analysis across (Wannack; Langley et al., 2023; Xia et al., 2025) demonstrates how distributed ledger technologies (DLTs) can underpin trust and verification within DPP systems. Blockchain architectures are shown to maintain data integrity and provide permanently auditable trails for cross organizational exchanges, a requirement particularly relevant to shipbuilding, where suppliers are geographically dispersed and component provenance is difficult to verify. These technologies also support standardized metadata structures that allow heterogeneous systems to communicate, facilitating interoperability between classification bodies, port authorities, and recycling facilities.

Studies (Foivos Psarommatis et al., 2024; Okumus et al., 2024) indicate measurable performance improvements where DPP frameworks are adopted. Documented benefits include reductions in resource consumption during retrofitting, higher accuracy in spare parts management, and more transparent reporting of environmental indicators. These findings are aligned with (Abdel-Aty et al., 2025) which shows that integrating passport data into remanufacturing workflows enhances component compatibility assessment and decreases material losses.

At the institutional level, (M. Nettelbladt and K. Stojanovski, 2024) identify the governance and human capital dimensions necessary for effective implementation. The study highlighted challenges in establishing shared data standards, aligning enterprise resource planning systems, and developing competencies in data analytics, digital ethics, and system interoperability. Such insights underline that DPP deployment in maritime contexts requires not only technological infrastructure but also organizational adaptation and workforce upskilling.

Finally, the synthesis across (van Capelleveen et al., 2023) and (Adisorn et al., 2021) suggests that the DPP functions as both a technical artefact and a governance mechanism. It mediates between policy expectations, industrial standards, and practical design constraints. Within maritime operations where international conventions and regional regulations coexist this mediating role can harmonize sustainability assessment and reporting practices across jurisdictions.

In summary, the existing body of research within the provided corpus converges on a shared conclusion: the Digital Product Passport is not merely an information tool but a cornerstone of a data driven circular economy. It connects product design, operation, and recycling through transparent information exchange, enabling maritime stakeholders to pursue environmental compliance, cost efficiency, and innovation simultaneously.

The Digital Product Passport as both a technological enabler and a governance mechanism for circularity and sustainability. By integrating lifecycle data with digital twins, distributed ledgers, and IoT systems, DPPs have the potential to transform the maritime industry's approach to traceability, compliance, and resource efficiency. In this context, the following sections examine how DPPs can be operationalized to foster material circularity, environmental performance, and improve decision-making across the shipbuilding, operation, and recycling stages.

2. Conceptual and Technological Foundations

The concept of the Digital Product Passport (DPP) originates from the need to bridge material traceability, data transparency, and lifecycle management within complex industrial systems. As clarified by Wicaksono et al., the DPP is not a single database but an interconnected system linking product identity, lifecycle events, and sustainability attributes across organizational boundaries. It relies on structured data models capable of integrating heterogeneous information from manufacturers, operators, and recyclers through interoperable digital infrastructures (Wicaksono et al., 2025).

The conceptual architecture outlined by Nettelbladt and Stojanovski defines the DPP as a multi-layer information framework composed of: product identification, lifecycle data aggregation, and environmental performance metrics (M. Nettelbladt and K. Stojanovski, 2024). The identification layer establishes a unique digital identity for each asset, while the data aggregation layer stores information related to materials, manufacturing processes, maintenance, and usage. The environmental layer encapsulates carbon footprint indicators, recyclability scores, and regulatory compliance attributes.

These studies emphasize that interoperability among stakeholders depends on adopting open data schemas and standardized communication interfaces. Based on metadata standards to harmonize data exchange across enterprise resource planning systems, reducing inconsistencies in reporting and minimizing duplication of effort (Zhang and Seuring, 2024). In maritime applications where components are sourced globally this modular and standardized structure allows data from shipyards, classification societies, and recycling yards to be consolidated within a unified digital record.

2.1. Enabling technologies

Technological enablers determine the scalability and trustworthiness of DPP systems. Blockchain enables immutable recording of transactions, certification of materials, and verifiable provenance trails (Xia et al., 2025). In maritime settings, these functions are particularly critical because ship components traverse multiple jurisdictions and ownership structures before decommissioning.

IoT networks on vessels can record performance metrics (Fareed et al., 2024), while AI models analyze these streams to predict component degradation or failure. The data are automatically synchronized with DPP entries, facilitating condition-based maintenance and reducing downtime. Table 1 summarizes the technological enablers underpinning DPP implementation within maritime contexts.

While technological readiness is important, successful deployment requires personnel trained in digital ethics, cybersecurity, and data governance. The study reports that gaps in digital literacy particularly in small and medium sized enterprises can hinder the consistent use of standardized data platforms (Papageorgiou, 2025).

The collaboration mechanisms such as data-sharing agreements and governance protocols must be codified to ensure equitable participation among stakeholders (Langley et al., 2023). Without such frameworks, the potential of DPPs to generate systemic circularity is limited by fragmented ownership of information.

2.2 Systemic integration

DPPs enable accurate mapping of material flows, which can improve waste reduction and resource optimization at the end-of-life stage (Lennartz et al., 2025). DPP data are integrated into production control and remanufacturing systems, measurable gains are achieved such as reduced lead times, improved material matching, and increased component reuse (Psarommatis and May, 2024; Abdel-Aty et al., 2025).

Adisorn et. al., mentions harmonized standards, open APIs, and cross sector pilot projects to demonstrate the feasibility of linking DPP infrastructures with existing industrial platforms (Adisorn et al., 2021). These insights are directly applicable to maritime operations, where DPP adoption must align with ship classification databases, environmental monitoring systems, and international reporting protocols.

Table 1. Technological Enablers of the DPP in Maritime Contexts.

Key Technologies	Operation Role (The Concept)	Supporting sources for the technologies
Unique digital IDs, QR/NFC tags, standardized metadata schemas	Links each ship component to its digital record; ensures traceability across ownership changes	(van Capelleveen et al., 2023; M. Nettelbladt and K. Stojanovski, 2024)
Cloud computing, ERP integration, IoT sensors	Collects lifecycle, maintenance, and operational data from distributed actors	(Fareed et al., 2024; Zhang and Seuring, 2024)
Blockchain and Distributed Ledger Technologies	Provides immutable records of material provenance and certification	(Wannack; Xia et al., 2025)
Artificial Intelligence, predictive analytics	Supports predictive maintenance, resource optimization, and carbon accounting	(Abdel-Aty et al., 2025; Koilo, 2025)
Data-sharing protocols, digital ethics frameworks, policy compliance tools	Defines responsibilities, ensures data protection, and aligns actors with sustainability standards	(Langley et al., 2023; Papageorgiou, 2025)

3. Digital Product Passports in Maritime Industry

The maritime industry represents a distinct industrial ecosystem characterized by heavy material dependency, long asset lifespans, and complex international logistics. Within this environment, Digital Product Passports (DPPs) act as a digital infrastructure connecting material, operational, and environmental data throughout the ship lifecycle. The maritime value chain from raw material procurement and component manufacturing to ship operation and end-of-life dismantling suffers from fragmented data visibility (Okumus et al., 2024). The implementation of DPP frameworks can mitigate these inefficiencies by establishing continuous traceability across supply chain tiers. (Foivos Psarommatis et al., 2024)

3.1 Material traceability and circular design

A core structural advantage of DPPs lies in their ability to enhance material traceability and promote circular product design. Lifecycle transparency begins at the material composition level (Rosado da Cruz and Cruz, 2025). DPPs enable designers and shipyards to register information such as alloy content, recycled material ratios, and hazardous substance profiles. When this data is standardized and accessible, ship components can be designed for easier disassembly and recycling, thus aligning with circular design principles.

Digital traceability facilitates resource recovery (Lennartz et al., 2025) at the end of a ship's operational life. Accurate material mapping allows dismantling yards to optimize separation processes, recover high-value metals, and minimize waste. These mechanisms not only reduce environmental impact but also generate financial incentives by linking material value retention with compliance reporting.

Senarathne et.al., focused on terrestrial infrastructure provides valuable analogies (Senarathne et al., 2025). It highlights how material passports can guide decision-making during reconstruction by identifying reusable aggregates and compatible material classes. The same principles apply to maritime structures, where modular design and traceable materials enable efficient repurposing of ship sections.

3.2. Maintenance, repair, and remanufacturing

Maritime operations depend heavily on preventive and corrective maintenance cycles. DPP data into maintenance management systems enables predictive insights and component level remanufacturing (Abdel-Aty et al., 2025). When IoT sensor data are synchronized with DPP records, performance anomalies can be detected early, allowing targeted interventions that extend component lifetimes.

DPPs support real-time condition monitoring and spare-part traceability (Foivos Psarommatis et al., 2024). Reduced downtime, lower spare inventory requirements, and increased reuse rates are documented benefits.

Remanufacturing processes also benefit from passport based data continuity. Incorporating DPP information into production planning improves component compatibility assessment and material matching during reassembly (Hermann et al., 2025). This reduces waste and ensures compliance with quality and safety standards during remanufacturing.

3.3. Supply chain and logistics optimization

From a systemic viewpoint, DPPs can work as catalysts for supply-chain synchronization (Fareed et al., 2024; Zhang and Seuring, 2024). They enable automated data exchange between shipyards, suppliers, and recyclers, thereby reducing redundancies and administrative bottlenecks.

Through the use of standardized data models and APIs, DPP enabled systems integrate seamlessly with enterprise resource planning platforms, ensuring that material declarations, certificates, and component histories can be verified in real time. DPPs create digital ecosystems where regulatory authorities, insurers, and customers can access verified sustainability data without compromising proprietary information (Langley et al., 2023).

This interconnected approach supports the maritime industry's transition from linear procurement cycles toward closed loop logistics, where material flows are monitored from cradle to grave.

Table 2. Functional Roles of DPPs Across Maritime Lifecycle Phases.

Lifecycle Phase	Function of DPP	Key Benefits	Supporting Sources
Design & Procurement	Material composition tracking, design-for-disassembly documentation	Improved circular design, compliance with sustainability criteria	(Lennartz et al., 2025; Rosado da Cruz and Cruz, 2025)
Manufacturing & Assembly	Process traceability, certification management	Reduced material losses, improved quality control	(Hermann et al., 2025; Wicaksono et al., 2025)
Operation & Maintenance	Condition monitoring, predictive maintenance, performance analytics	Extended asset life, optimized maintenance planning	(Abdel-Aty et al., 2025; Koilo, 2025)
Remanufacturing & Repair	Component compatibility verification, reuse tracking	Higher reuse rates, reduced environmental impact	(Foivos Psarommatis et al., 2024; Okumus et al., 2024)
End-of-Life Recycling	Material inventory management, hazardous material traceability	Improved recycling efficiency, regulatory compliance	(Psarommatis and May, 2024; Bhati et al., 2025)

3.4. End-of-life and recycling processes

The end-of-life stage represents one of the most challenging phases in the maritime lifecycle due to the complexity of ship dismantling and hazardous material handling. DPPs can transform ship recycling by embedding disassembly plans, material inventories, and environmental risk data into digital twins accessible to shipyards and recycling yards (Okumus et al., 2024; Bhati et al., 2025).

The integration of accurate material flow models has been associated with higher recovery rates, reduced contamination, and improved documentation quality indicating that the digital infrastructure directly contributes to sustainability performance.

3.5. Organizational and collaborative structures

Beyond the technical layer, the literature emphasizes the structural governance required to sustain DPP deployment. The functional contributions of DPPs across the maritime product lifecycle are summarized in Table 2. Organizational alignment, digital literacy, and shared governance are indispensable for the effective use of DPPs (Papageorgiou, 2025).

4. Conclusions and Recommendations

Digital Product Passports (DPPs) can be a transition tool for the maritime sector by enhancing transparency, traceability, and circularity. DPP consolidates detailed information regarding the materials, operations, and environment of maritime assets over their entire lifecycle. This connection optimizes resource use and enables individuals to make informed decisions regarding ship design, maintenance, and end-of-life management based on data.

Blockchain, the Internet of Things (IoT), and cloud computing collaboratively enable real-time verification, ongoing monitoring, and secure information transmission. These characteristics enable shipbuilders, operators, and recyclers to collaborate utilizing shared, validated datasets rather than fragmented documentation.

The DPP serves as a mechanism for institutional collaboration, in addition to being a technological advancement. DPPs are digital governance platforms that ensure company operations align with policy objectives. They bridge the gaps among regulators, supply chain stakeholders, and sustainability auditors by ensuring clarity and accountability.

The assessments for each sector demonstrate quantifiable operational advantages, including improved product life cycle tracking, reduced waste, remanufacturing efficiency, and enhanced accuracy in environmental reporting.

These modifications promptly advance the objectives of European sustainability frameworks for decarbonization and material circularity.

Digital capability building is important for realizing the DPP benefits at the organizational level. Individuals employed at shipyards, classification societies, and port authorities must acquire proficiency in data management, online safety, and adherence to digital ethics. DPPs not only develop technical infrastructure but also necessitate a cultural shift towards collaborative data-driven practices.

From a commercial perspective, including DPPs into service-oriented models enables enterprises to generate revenue through other avenues, including the provision of maintenance services, performance monitoring, and obtaining sustainability certifications. This alteration shifts value creation from the quantity produced to optimizing the product's lifespan.

Regulatory frameworks that integrate DPP requirements into existing marine reporting systems, such as those established in the EU Ship Recycling Regulation. Establishing uniform standards for metadata, interoperability, and data ownership will reduce many issues currently hindering business engagement.

Collaboration between the public and private sectors is also essential. Multi-stakeholder coalitions can unite regulators, technology providers, and business organizations to evaluate DPP procedures. Pilot projects financed by European research initiatives provide methods for scaling collaborative implementation while maintaining innovation and compliance.

The marine industry's implementation of Digital Product Passports represents an advancement towards a digitally enabled circular economy. The analyzed data indicates that DPPs can improve material traceability, operational efficiency, and compliance transparency when supported by standardized governance and technological frameworks. To attain these advantages, collaboration among stakeholders in policy, business, and academia is essential.

The marine sector might evolve its approach to sustainability from disjointed reporting and reactive maintenance to cohesive, predictive, and data-validated lifecycle management by incorporating digital transformation with circular design principles. DPPs serve not only as instruments for efficiency but also play a role in accountability and fostering innovation within the blue economy.

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CHAPTER 9

SUSTAINABLE DEVELOPMENT GOALS AND SHIPBUILDING: ANALYSIS OF SDG-EDUCATION NEXUS FROM AN INDUSTRY PERSPECTIVE

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Abstract

This study addresses the need and potential of the Naval Architecture and Marine Engineering curriculum to foster awareness and responsive behavior toward major challenges, for instance, global warming, water pollution, and industrial transformation, through the lens of industry demands. In this context, aligning global needs with sectoral expectations necessitates the integration of these themes into engineering education.

Keywords: Sustainable development goals; Naval architecture and marine engineering curricula; Education and industry.

1. Introduction

The uptake of the United Nations' (UN's) Sustainable Development Goals (SDGs) in 2015 identified a critical milestone in shaping global policy, educational priorities, and industrial strategies. Organized into 17 overarching goals and 169 specific targets, seen in Table 1, the SDGs constitute a comprehensive agenda that calls upon governments, universities, industries, and civil society worldwide to collaborate for a sustainable future (UN, 2015). Their scope is wide-ranging, covering the eradication of poverty, the promotion of clean energy, climate action, and the protection of life below water, among others. Within this framework, engineering disciplines are expected to assume a leading role in devising solutions to these global challenges. The maritime sector, which accounts for more than 80% of international trade, and its related field of shipbuilding, occupy a particularly strategic position due to their dual role as major drivers of economic activity and significant contributors to environmental impact (Álvarez, 2021; Alamoush & Ölçer, 2021).

The SDGs are not the UN's first global development initiative. In 2000, as a previous attempt the "Millennium Development Goals" (MDGs) were introduced, comprising eight goals and 21 targets aimed at reducing poverty, achieving gender equality, enhancing the well-being of mothers and children, and preventing and managing conditions like HIV/AIDS and malaria, with a 2015 deadline (UN, 2000). While the MDGs achieved progress in several areas, they were limited in scope, particularly regarding environmental sustainability and the integration of industrial and infrastructural dimensions. The SDGs expanded upon this foundation by offering a broader and more holistic vision. In this context, the maritime and shipbuilding industries have experienced significant transformations, spurred not only by the global sustainability agenda but also by new international regulations focusing on emissions and resource efficiency.

The intellectual roots of both the MDGs and SDGs lie in earlier global debates. The Brundtland Report of 1987 (Our Common Future) introduced the within academic literature, sustainable development is often characterized as development that reconciles present consumption and resource use with the long-term capacity of future generations to sustain themselves. It also articulated the three main pillars of this objective including balanced progress across economic, social, and environmental dimensions (WCED, 1987). The three pillars of the SDGs are shown in Figure 1. This framework has shaped subsequent UN agendas and remains central to sustainability discourse. Building on this foundation, the 1992 Rio Earth Summit produced Agenda 21, the first global and serious action plan explicitly seeking to balance environmental concerns with developmental goals (UN, 1992). Thus, the SDGs inherited the legacy of the MDGs while consolidating the three-pillar model into a more comprehensive and globally coordinated strategy.

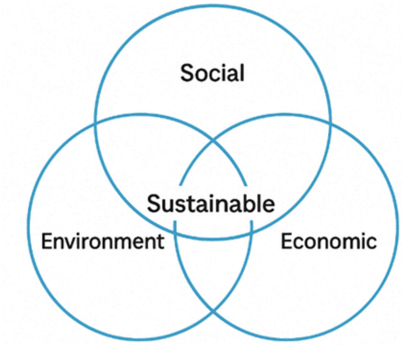

Figure 1. Three Pillars of Sustainable Development Goals.

Table 1. UN's Sustainable Development Goals.

SDG no	SDGs	Keywords
SDG 1	No poverty	Economy, social security, disasters
SDG 2	Zero hunger	Social security, disasters
SDG 3	Good health and well-being	Safety, physical education, health, disaster
SDG 4	Quality education	Skills (Practical, manual, language and academic)
SDG 5	Gender equality	Rules, regulations, law, ethics
SDG 6	Clean water and sanitation	Water, sea, sanitation, ecology, environment, disasters

SDG 7	Affordable and clean energy	Energy, energy generation, energy efficiency
SDG 8	Decent work and economic growth	Ethics, safety, advising, rules, regulations, law, economy, finance, human resource
SDG 9	Industry, innovation and infrastructure	Industry, innovation, infrastructure
SDG 10	Reduced inequalities	Reduced inequalities
SDG 11	Sustainable cities and communities	Law, environment, society, safety, quality
SDG 12	Responsible consumption and production	Energy efficiency, consumption theory, design
SDG 13	Climate action	Environment, disasters, innovative technologies, clean energy
SDG 14	Life below water	Disasters, rules, regulations, environment, ecology
SDG 15	Life on land	Environment, disasters
SDG 16	Peace, justice and strong institutions	Advising, rules, regulations, law, economy, ethics, disasters
SDG 17	Partnerships for the goals	Advising

Education plays a pioneering role in progress of this agenda by shaping the knowledge, values, and skills of future generations. SDG 4 (Quality Education) is both an independent goal and an enabling instrument for the succession of all other targets (Reimers, 2024). Education thus serves as both a final target and an efficient tool within the sustainable development framework. Universities, in particular, cannot be viewed merely as institutions of knowledge transfer; they also act as incubators of social transformation, critical thinking, and technological innovation. For this reason, embedding SDGs within higher education has become a priority worldwide. Nonetheless, evidence shows that universities' efforts often remain fragmented, characterized by awareness campaigns rather than robust, long-term institutional strategies (Leal Filho et al., 2019; 2021; 2023). Barriers include insufficient incentives for faculty engagement and structural constraints that complicate the implementation of sustainability initiatives.

Empirical studies confirm these challenges. Leal Filho and colleagues (2021), surveying 28 universities across 21 countries, found that while awareness of

SDGs was widespread, translating this awareness into strategic action was inconsistent. A broader study of 279 universities in 45 countries (Leal Filho et al., 2019) indicated that most institutions had developed sustainability strategies, yet these were often superficial and disconnected from operational plans. Another international survey of academics across 65 countries (Leal Filho et al., 2023) reported that SDG-related content is increasingly integrated into teaching and research, but that student demand for such content remains weak. Although the impact of these shortcomings may vary by discipline, they pose a particular challenge in engineering fields, such as naval architecture and marine engineering, where the stakes for technological and environmental innovation are especially high.

There are, however, encouraging signs of progress. Xue (2022), analyzing Times Higher Education (THE) Impact Rankings, documented a rapid increase in university participation in SDG-related activities, rising from 467 institutions in 2019 to more than 1,400 in 2022. Furthermore, while early efforts emphasized SDG 3 (Health) and SDG 4 (Education), recent trends highlight SDG 9 (Industry, Innovation, and Infrastructure), suggesting a growing alignment with engineering and industrial priorities. Reimers (2024) cautions, however, that despite notable advances in SDG 4, significant global gaps persist in financing, lifelong learning, and adaptation to new technologies. For dynamic fields such as shipbuilding, this underscores the necessity of continually updating curricula to reflect evolving regulatory and technological landscapes.

Disciplinary studies also highlight varying levels of engagement. In nursing and radiography, curricula have been updated in line with SDG 3 (Health and Well-being), fostering competencies in global citizenship and health equity (Upvall & Luzincourt, 2019; Chau et al., 2025). In architecture, efforts have primarily centered on SDG 11 (Sustainable Cities and Communities), while integration of other goals has been limited (Hendawy et al., 2024). Business education research demonstrates that project-based and experiential learning approaches linked to SDGs strengthen students' ethical reasoning and sustainability awareness (Leal Filho et al., 2021; 2023). These findings reinforce the argument that engineering education should similarly embed sustainability not only at the technical level but also as a set of values and practices shaping professional identity.

The maritime industry provides striking examples of the intersection between SDGs, regulation, and engineering design. Álvarez (2021) highlighted the IMO 2020 sulfur cap and reforms in salvage law as milestones that integrate environmental sustainability into maritime governance. IMO 2020 directly supports SDG 13 (Climate Action) and SDG 14 (Life Below Water) by mandating a drastic reduction in sulfur emissions. These policies have forced ship designers and engineers to innovate in fuel technology, exhaust gas treatment systems, and alternative propulsion methods, including LNG, methanol, and ammonia. In addition, instruments as given in the following; The Energy Efficiency Design Index (EEDI) and Energy Efficiency Existing Ship Index (EEXI) align closely with SDG 7 (Clean Energy) and SDG 9, placing efficiency and innovation at the core of maritime engineering education.

At the same time, sustainability in ports and shipbuilding continues to reveal imbalances. Reviewing the literature, Alamoush and Ölçer (2021) found that environmental initiatives dominate port sustainability efforts, while social and economic aspects are often overlooked. A similar pattern exists in shipbuilding, where technical measures, such as fuel transition and improvements in efficiency, receive priority, but issues of occupational safety, social inclusion, and economic resilience lag behind. The three-pillar model (WCED, 1987) reminds us that true sustainability requires balance across all dimensions, not just environmental progress.

Taken together, the literature points to three key insights. First, SDG integration in higher education remains fragmented and requires comprehensive institutional frameworks (Leal Filho et al., 2021; 2022; 2023). Second, experiential, student-centered pedagogies have proven effective in deepening sustainability awareness (Leal Filho et al., 2023). Third, in sectors such as shipping and shipbuilding, regulatory initiatives are not merely complementary but are actively reshaping industrial practices and engineering curricula (Álvarez, 2021). For this reason, embedding SDGs into shipbuilding and marine engineering education is both a necessity for global compliance and an opportunity to position the discipline as a crucial player of sustainable development.

2. Methodology: Conceptualizing the gap between education and industry needs

Conceptualizing the gap between traditional education and the needs of the shipbuilding industry involves identifying the mismatches between the knowledge, skills, and competencies provided by academic curricula, particularly within the scope of engineering education, and the requirements of the labor market. This conceptualization provides a framework for aligning educational outcomes with industrial expectations, fostering collaboration, and achieving the objectives encompassed within the scientific domain in line with the Sustainable Development Goals.

2.1. Introduction and contextual framework

Naval architecture and marine engineering represent a critical discipline for the maritime industry. The education provided in this field carries strategic importance not only for economic development but also for ensuring environmental continuity. Technological transformations in the sector, such as green ship designs, alternative fuels, and digitalization, necessitate a reconfiguration of engineering curricula. This educational transformation is directly aligned with the 17 Sustainable Development Goals (SDGs) declared by the United Nations in 2015 (UN, 2015).

The shipbuilding industry is intrinsically linked to multiple SDGs, particularly SDG 7, SDG 9, SDG 12 SDG 13 and SDG 14 (Affordable and Clean Energy), (Industry, Innovation and Infrastructure), (Responsible Consumption and Production), (Climate Action), (Life Below Water). Therefore, the education of future naval architecture and marine engineers must encompass not only technical competencies but also a strong awareness of environmental and societal responsibilities.

2.2. Industrial expectations and their alignment with SDGs

The maritime industry increasingly demands engineers who can adapt to complex design and production systems, integrate digital and environmentally conscious approaches, offer innovative solutions, think systematically, and collaborate across disciplines. In this context, the primary expectations of the shipbuilding industry from engineering graduates can be summarized as follows:

Energy efficiency and knowledge of alternative fuels: In line with SDG 7 and SDG 13, there is a growing emphasis on the use of alternative propulsion systems such as methanol, LNG, hydrogen, and hybrid technologies in ships (DNV, 2014). The integration of these innovations into ship systems is expected to enhance process efficiency through environmentally friendly solutions. Ensuring workplace safety and occupational health while optimizing production aligns with the Decent Work and Economic growth which is included in SDG 8.

Emission reduction techniques: Associated with SDG 12 and SDG 13, reducing carbon emissions, implementing energy recovery systems, and adopting life cycle assessment (LCA) practices are key areas where engineers must be proficient. In particular, it is crucial for those involved in the design and optimization of marine energy systems to receive targeted education in these areas.

Environmental improvements in shipyard operations: Beyond on-board systems, sustainable practices must be implemented in shipyards as well. Within this framework, green shipyard practices, as emphasized in SDG 9 and SDG 12, promote resource efficiency, waste minimization, and recycling throughout the production process. These approaches contribute directly to multiple SDGs by reducing environmental impact and material waste through streamlined and accurate production processes.

Digital transformation and Industry 4.0 integration: The application of digital technologies, such as digital twins, AR/VR systems, and the Internet of Things (IoT), to increase automation and efficiency in shipyards aligns with the objectives of SDG 9 as in the Industry referring Innovation and Infrastructure development. .

Environmental protection for marine ecosystems: In alignment with SDG 14 (Life Below Water), environmentally sensitive design approaches are expected to mitigate pollution risks originating from ship operations and shipbuilding activities.

2.3. Current status: the SDG coverage of naval architecture education

An analysis by Zincir (2022) revealed that the training of marine engineers, particularly those involved in ship operations, showed strong alignment with Quality Education, included in SDG 4, SDG 7, SDG 9, and SDG 12. However, the study also found limited integration with more socially oriented goals such as SDG 1 (No Poverty), SDG 2 (Zero Hunger), SDG 10 (Reduced Inequality), and SDG 17 (Partnerships for the Goals) (Zincir, 2022). The study conducted by Dere and Bulut (2024) evaluates how effectively naval architecture and marine engineering curricula align with the UN's Sustainable Development Goals and the International Maritime Organization's (IMO) educational priorities. The research reveals that current programs exhibit partial integration of sustainability themes, with stronger emphasis on technical goals such as clean energy (SDG 7), infrastructure and innovation (SDG 9), and sustainable production (SDG 12). However, there is limited engagement with socially focused goals like gender equality (SDG 5) and reduced inequalities (SDG 10). Using a course-level mapping approach, the study identifies curriculum strengths in environmental protection and safety, but also points to gaps in climate action (SDG 13) and marine ecosystem health (SDG 14). The authors recommend targeted reforms, including the introduction of interdisciplinary sustainability modules, project-based learning, and greater coverage of alternative fuel systems and emission reduction strategies. Overall, the study highlights the need for a more structured and SDG-oriented framework to better prepare engineers for the evolving demands of the maritime sector. This finding suggests that despite growing awareness, a systematic integration of SDGs into engineering curricula remains insufficient.

3. Results and Discussion: Alignment between Maritime Industry Demands and SDG-Based Engineering Education

A critical evaluation of the current naval architecture and marine engineering curricula in relation to both the Sustainable Development Goals (SDGs) and the expectations of the maritime industry reveals a limited but promising alignment. The analysis indicates that certain curriculum components reflect global sustainability priorities and technological shifts. However, substantial gaps remain, particularly in addressing interdisciplinary competencies, socio-environmental dimensions, and institutional adaptability.

Strengths: Technical Coherence and Emerging Integrations; Current engineering programs demonstrate strength in addressing technical SDGs such as SDG 7, SDG 9, and SDG 12. These align with industrial demand for energy efficiency, fuel flexibility, and lifecycle-based ship design practices. The inclusion of propulsion systems, hull optimization, structural reliability, and material science reflects the foundational knowledge needed for environmentally efficient and economically viable vessel design. Furthermore, a growing number of curricula have begun integrating digitalization modules—e.g., computer-aided design (CAD), basic simulation tools, and limited applications of digital twins. These developments partially support the industry's transition toward smart shipyards, automated production lines, and data-driven design verification, which are key aspects of the maritime sector's Industry 4.0 transformation.

Weaknesses: Limited Environmental Depth and Interdisciplinary Breadth; Despite these strengths, the curricula generally lack depth in climate-centered and ocean-centric objectives such as SDG 13 and SDG 14. Topics such as maritime carbon footprints, ecological impact assessments, ballast water management, and circular design principles are not systematically embedded into the learning outcomes. Similarly, SDG 5 and SDG 10 remain underrepresented, reflecting a broader neglect of socio-technical contexts in engineering education. Additionally, there is a mismatch between industry expectations for adaptive, system-thinking engineers and the static structure of many university curricula. The sector increasingly demands professionals capable of managing complexity, operating in interdisciplinary teams, and adopting holistic problem-solving frameworks that consider not only performance and cost, but also regulatory, environmental, and safety constraints.

Institutional Barriers and Structural Challenges; Barriers to curriculum reform include rigid accreditation structures, limited faculty specialization in emerging technologies, and insufficient university and industry interaction. Moreover, implementing modules on hydrogen-based propulsion, green retrofitting, or AI-assisted diagnostics often requires substantial infrastructure, academic retraining, and cross-disciplinary coordination. These challenges are exacerbated in public universities where resource allocation and curricular flexibility are constrained.

Strategic Solutions: Curriculum Reform and Competency Development; To bridge these gaps, a strategic curriculum reform is imperative. First, the integration of interdisciplinary electives involving environmental science, data analytics, maritime law, and public policy will equip future engineers with the cognitive tools to engage with sustainability in practice. Second, project-based learning models, co-developed with industry partners, can enhance experiential learning and directly address real-world challenges aligned with SDG frameworks. Third, the development of modular and adaptive course structures can allow for rapid incorporation of technological advancements and sectoral trends. This will enable universities to respond proactively to IMO regulations, decarbonization initiatives, and innovation demands. Finally, national accreditation bodies must revise standards to facilitate such agile curriculum models and incentivize sustainability-oriented outcomes. The roadmap of the evolution of the curricula is presented in Figure 2.

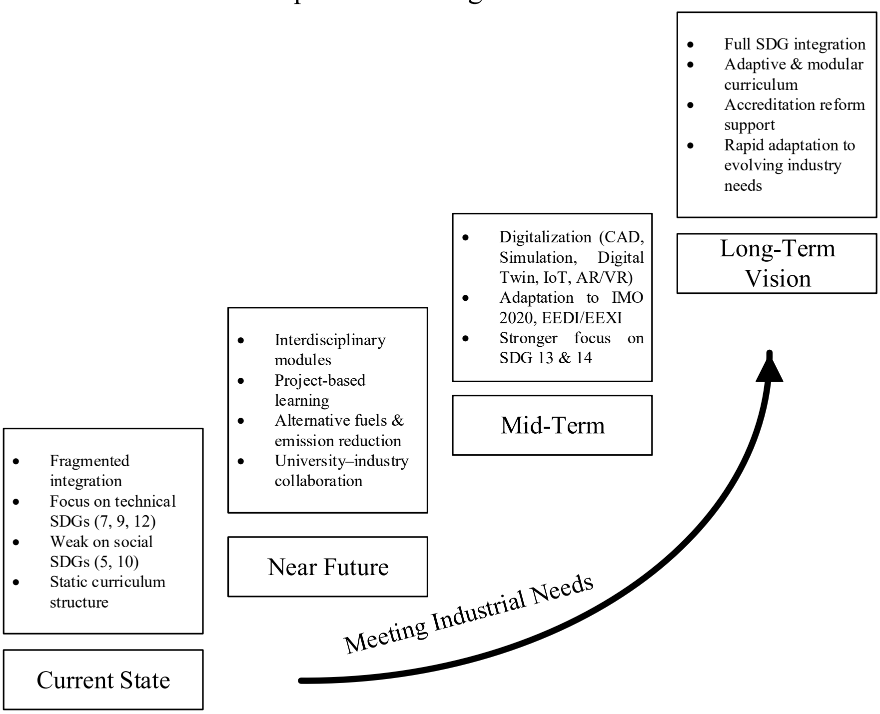

Figure 2. Projected Transformation of the Curriculum of Naval Architecture and Marine Engineering.

The roadmap outlines a phased transformation of Naval Architecture and Marine Engineering curricula. The current state is fragmented, with strong emphasis on technical SDGs but weak integration of social aspects. The near future introduces interdisciplinary learning, industry collaboration, and focus on alternative fuels. Mid-term priorities include digitalization and compliance with international regulations. The long-term vision targets full SDG integration, modular structures, and rapid adaptation to industry needs.

While immediate and full-scale integration of SDG targets into engineering curricula may not be feasible due to institutional and systemic limitations, a phased and collaborative approach that aligns educational frameworks with industrial transformation pathways offers a sustainable and scalable roadmap.

4. Conclusion

Naval architecture and marine engineering education exhibits partial alignment with the Sustainable Development Goals. However, comprehensive and systematic transformation is only possible through curriculum reform, industrial collaboration, and robust evaluation mechanisms. In particular, it is essential to embed environmental and social awareness into engineering education with regard to climate change, ocean health, and energy transition. To produce engineers who are capable of addressing global sustainability challenges, educational institutions must adopt SDG-oriented strategic planning. This includes fostering system thinking, embracing technological innovation, and nurturing a strong sustainability mindset. Without such an approach, future engineers may lack the interdisciplinary capacity and environmental ethics required to contribute meaningfully to sustainable maritime development.

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CHAPTER 10

OSCILLATING APPENDAGES: A DEBATE ON THE HIDDEN SOURCES OF DRAG IN NAVAL ARCHITECTURE

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Abstract

In the pursuit of enhanced efficiency in naval architecture, the hydrodynamic drag of the main hull has historically been the primary focus, often leaving the resistance from ship appendages—such as fins, rudders, and bilge keels—underestimated. This book chapter argues that the dynamic, oscillatory motions of these components, driven primarily by Vortex-Induced Vibrations (VIV), constitute a significant and frequently overlooked source of "hidden drag". We first establish the baseline of static appendage drag before delving into the fundamental physics of VIV, including the von Kármán vortex street and the critical "lock-in" phenomenon, where appendage motion synchronizes with vortex shedding, leading to large-amplitude oscillations. A comprehensive review of experimental and computational fluid dynamics (CFD) literature reveals a consistent finding of "drag amplification", where the mean drag coefficient of an oscillating appendage can more than double compared to its stationary state. The central conclusion is that a purely static analysis of appendage drag is inadequate for predicting vessel performance and structural integrity. The paper calls for a paradigm shift towards a dynamic, fluid-structure interaction (FSI) framework and highlights the urgent need for further research, paving the way for the design of more efficient vessels.

Keywords: Ship Appendages, Hydrodynamic Drag, Vortex-Induced Vibrations (VIV), Flow-Induced Vibrations (FIV), Drag Amplification.

1. Introduction: The Unseen Cost of Hydrodynamic Drag

In the relentless pursuit of efficiency in naval architecture, the primary focus has historically been on optimizing the hull form to minimize resistance. For decades, naval architects and hydrodynamicists have meticulously refined hull lines, perfected bulbous bows, and streamlined superstructures to ensure vessels slice through water with the least possible opposition. This focus on the macroscopic elements of ship design has yielded significant gains in fuel efficiency and speed. However, as the industry pushes the boundaries of performance and sustainability, a more granular analysis of hydrodynamic drag reveals that substantial, often-unaccounted-for, resistance originates from sources previously considered secondary: the vessel's own appendages. This chapter, "Oscillating Appendages: A Debate on the Hidden Sources of Drag in Naval Architecture", delves into these frequently overlooked contributors to total ship resistance.

Appendages such as rudders, propellers, stabilizer fins, and bilge keels are essential for maneuverability, stability, and propulsion. Yet, their dynamic, often oscillatory, motions introduce complex hydrodynamic phenomena that result in significant energy losses. A rudder held at aft in calm water contributes a predictable amount of frictional drag; that same rudder, when actively deflecting to maintain course in a seaway, generates a far more complex and amplified resistance profile. This is due to unsteady flow effects, including vortex shedding and dynamic pressure changes, which are fundamentally different from the steady-state drag components traditionally analyzed.

The core argument of this chapter is that a comprehensive understanding of ship hydrodynamics requires a dedicated focus on these unsteady, motion-induced drag components. We will explore the theoretical underpinnings of oscillating flow, examining how the frequency and amplitude of appendage motion interact with the fluid to create forces that resist a vessel's surge. Furthermore, we will present experimental data and computational fluid dynamics (CFD) simulations from literature that quantify the magnitude of this "hidden drag", revealing it to be a critical factor in the overall energy consumption of a modern vessel, particularly in realistic operational conditions. By shining a light on these unseen forces, we aim to provide naval architects with the knowledge and tools necessary to design and operate vessels that are not only efficient in calm seas but are truly optimized for the dynamic reality of the maritime environment.

This chapter lays the groundwork by emphasizing the critical importance of reducing ship resistance. It links the large-scale challenges faced by the global maritime industry—such as rising fuel costs and stringent environmental regulations—to the small-scale yet vital hydrodynamic effects occurring at the component level. The introduction then shifts focus from the well-known issue of static drag caused by appendages to the central argument of this study: that the dynamic, oscillatory motions of these components, primarily driven by Vortex-Induced Vibrations (VIV), represent a significant and often underestimated source of energy loss.

1.1 The global imperative for ship efficiency

Maritime transport serves as the keystone of global commerce, a tremendous industry responsible for conveying 95% of the world's cargo (Ahmadzadehtalatapeh & Mousavi, 2015). The economic and environmental impacts of such large-scale operations are correspondingly substantial. A staggering 85% to 95% of a cargo vessel's energy expenditure is dedicated solely to overcoming the hydrodynamic forces that enforces its transit through water (Ahmadzadehtalatapeh & Mousavi, 2015; Notteboom & Carriou, 2009). This positions hydrodynamic drag as the single most decisive factor in determining a ship's operational costs and its environmental footprint. For medium-speed vessels such as tankers, frictional resistance alone can constitute over 80% of the total drag.

The implications of this energy consumption are twofold. First, fuel represents one of the largest single operational expenditures for a vessel. Consequently, even marginal reductions in drag can yield substantial financial savings. It has been estimated that a mere 1% reduction in drag can result in annual savings of hundreds of thousands of dollars per vessel and lead to significant reductions in carbon-dioxide (CO2) emissions. Second, increasingly rigorous emissions standards from regulatory bodies like the International Maritime Organization (IMO) are compelling the maritime industry to pursue decarbonization (Pallàs, 2025). In this context, drag reduction is not merely an exercise in economic optimization but a fundamental requirement for environmental compliance and long-term sustainability (Lassesson & Andersson, 2009). This imperative provides a compelling rationale for the attentive examination of every potential source of drag, irrespective of its apparent magnitude.

As the maritime sector transitions toward more costly alternative fuels, the economic value of each efficiency gain is entrenched. This elevates the investigation of "hidden" drag sources, such as VIV, from a matter of academic interest to one of strategic urgency for ship owners and operators. A doubling or tripling of fuel costs commensurately increases the monetary value of even marginal efficiency gains. This economic multiplier effect underscores the pivotal role of hydrodynamic efficiency in the future competitiveness of maritime transport.

1.2 Ship appendages: a known contributor to drag

Structures that extend beyond the primary contours of a ship's hull, including rudders, bilge keels, propeller shafts, and their supporting struts, are collectively termed ship appendages. The usage of these components is indispensable for a vessel's maneuverability, stability, propulsion, and operational functions (John et al., 2012). From a hydrodynamic standpoint, however, these appendages represent an inherent source of resistance. Even in a static, non-oscillating state, appendages contribute significantly to the total ship resistance. For naval vessels, this contribution is estimated to range from approximately 2% to 14% of the total drag (U.S. Naval Academy, 2020). This resistance primarily originates from two principal components: viscous friction drag, which arises from the increased wetted surface area of the appendages, and pressure (or form) drag, which results from flow separation, particularly around bluff or poorly faired appendages (John et al., 2012; U.S. Naval Academy, 2020). This constitutes the baseline understanding of appendage drag and serves as a reference point for the additional complexities introduced by dynamic effects.

1.3 Uncovering oscillation-induced drag

The novel argument of this book chapter posits that while the static drag of appendages is routinely accounted in design methodologies, the dynamic response of these components to fluid flow presents a more complex and unexpected challenge. The principal mechanism underlying this dynamic response is Vortex-Induced Vibrations (VIV), a branch of Fluid-Structure Interaction (FSI) phenomenon (Williamson & Govardhan, 2004; Sarpkaya, 2004). When an appendage begins to oscillate under the influence of the surrounding flow, it fundamentally alters the local flow field. This gives rise to a phenomenon widely termed "drag amplification" in the literature, wherein the mean drag coefficient increases to a value substantially greater than that of the appendage in its static condition. This increased drag imposes a hidden energy penalty, compromising both fuel efficiency and structural integrity.

This reveals an intriguing debate in naval architecture. Many appendages, such as fin stabilizers and bilge keels, are engineered as "motion inhibitors" to mitigate large-scale motions like ship roll (John et al., 2012; Dai et al., 2009). Yet, these very components can become the source of high-frequency, detrimental oscillations (VIV) that degrade performance. The fact that a device designed to resolve one motion problem may inadvertently lead to another—one that elevates drag and induces fatigue—highlights the intricate nature of hydrodynamic design and the potential for unintended consequences. This book chapter concludes by outlining the subsequent sections, which delves into the physics of VIV, present a critical analysis of the evidence for drag amplification, and discuss the practical implications for the field of naval architecture.

2. A Hydrodynamic Assessment of Hull Appendages

Before delving into the complexities of oscillating motions, it is essential to establish a baseline understanding of the hydrodynamic role of various hull appendages in their steady or quasi-steady states. Hull appendages are external components attached to the main hull for specific functions, ranging from propulsion and maneuvering to stability enhancement. While indispensable for a vessel's operation, each appendage introduces a hydrodynamic penalty by increasing the wetted surface area and interrupting the smooth flow of water around the hull, thereby contributing to the total resistance.

2.1 Categorization of appendages

The most common appendages can be categorized by their primary function:

Control Surfaces: This category is dominated by rudders and stabilizer fins. A rudder is a foil-shaped surface located at the stern, used to generate lateral force to steer the vessel. Stabilizer fins, often retractable, are located near the turn of the bilge and are actively controlled to counteract and dampen the ship's rolling motion. In steady, straight-line sailing, these surfaces are aligned with the flow and primarily contribute frictional drag, but their foil shape also generates form drag.

Propulsion Systems: The propeller is the most ubiquitous propulsor, but this category also includes propeller shafts, supporting struts, nozzles, and azimuthing pods. While their purpose is to generate thrust, these components themselves are significant sources of drag. The complex geometry of propeller blades and the rotational flow they induce create a highly turbulent wake, and the supporting structures add their own frictional and pressure drag.

Stability and Flow-Modifying Devices: Bilge keels are long, narrow fins attached along the turn of the bilge on both sides of the hull. Their primary function is to increase hydrodynamic damping of roll motion. As passive devices, they are fixed in place and contribute drag continuously through friction and the generation of vortices as the ship rolls, even in slight seas. Other devices can include flow-directing fins or bossings designed to improve wake characteristics into the propeller.

Specialized Equipment: Many vessels are fitted with additional appendages for specific missions. Sonar domes, often bulbous protrusions on the bow or keel, house acoustic equipment and must be carefully designed to minimize their own resistance and flow noise. Thruster tunnels, which house transverse propellers for low-speed maneuvering, create large openings in the hull that generate significant drag, especially at transit speeds, due to pressure differences and vortex shedding from the tunnel edges.

Collectively, the added resistance from these appendages in a calm, straight-line transit can account for a substantial fraction—often cited as between 10% and 20%—of the total bare-hull resistance (Lewis, 1989). This baseline drag is a well-understood and accepted trade-off for the functionality they provide. However, the central theme of this work is that this steady-state assessment is incomplete. The true hydrodynamic cost of these appendages is only revealed when their dynamic, oscillatory movements in a realistic seaway are taken into account, a topic we will explore in the subsequent sections.

2.2 Components of static appendage drag

When appendages are not oscillating, they contribute to the total drag of the ship through several mechanisms. Understanding these static drag components is crucial for appreciating the additional burden imposed by dynamic effects.

Frictional Drag: This is the most direct drag component, arising from the increase in the total wetted surface area of the hull-appendage system. The addition of appendages increases the surface area in contact with the water, thereby increasing viscous friction forces (U.S. Naval Academy, 2020).

Pressure (Form) Drag: This type of drag results from pressure differences caused by the separation of flow from an appendage surface. Blunt bodies or appendages with sharp corners and poor hydrodynamic shaping experience significant flow separation, leading to substantial form drag (John et al., 2012).

Interference Drag: This complex component arises from the interaction of the flow fields between the hull and an appendage, or between multiple appendages. This interaction can be either detrimental or beneficial. For example, an A-bracket can negatively impact propulsive efficiency by constricting the flow between its strut arms and creating undesirable wake peaks at the propeller inflow. Conversely, some appendages, like wake adaptive fins, are specifically designed to improve propulsive efficiency by conditioning the flow ahead of the propeller disk, creating a favorable interference (Dai et al., 2009).

Established methodologies exist for calculating and scaling these static drag components, allowing for their estimation in the early stages of ship design.

3. The Physics of Flow-Induced Oscillation: Vortex-Induced Vibrations

This section provides a detailed technical explanation of the VIV mechanism. It is critical for understanding why appendages oscillate and how this self-sustaining process is governed by fundamental principles of fluid dynamics.

3.1 The origin of oscillation: the von Kármán vortex street

When flow passes a blunt body, such as a ship appendage, a boundary layer forms near the body's surface due to the fluid's viscosity. As the flow proceeds around the body, this boundary layer separates through the surface of the body. This separation leads to the formation and shedding of alternately rotating vortices in the wake of the body (Pai & Hay, 1988). This periodic vortex shedding creates a distinct wake pattern known as the "von Kármán vortex street". This pattern is clearly visible in visualizations from PIV or CFD simulations (SimFlow, 2025).

The periodic shedding of these vortices creates an alternating pressure differential on the two sides of the body. This pressure differential results in a periodic lift force (F_L) acting perpendicular to the flow direction and a fluctuating drag force (F_D) acting in the direction of the flow. For an elastically supported appendage, this periodic lift force is the primary driving force that initiates and sustains the oscillation (Crespi, 2017; ITTC, 2008).

3.2 Quantifying the phenomenon: The Strouhal number

The frequency of the vortex shedding phenomenon is characterized by the dimensionless Strouhal number (St). The Strouhal number associates the flow velocity (U), the vortex shedding frequency (f_s), and a characteristic dimension of the body (e.g., the diameter, D, for a cylinder):

$$St = \frac{f_s D}{U} \quad (1)$$

For a circular cylinder, the Strouhal number is remarkably constant at approximately 0.2 over a wide range of subcritical Reynolds numbers (Duranay et al., 2024). This predictability is key to anticipating when VIV might occur. Given the geometry of an appendage and the flow velocity it experiences, the forcing frequency created by vortex shedding can be estimated using this simple relationship.

3.3 The 'Lock-In' phenomenon: synchronization and amplitude amplification

The most critical concept in VIV is the emergence of "lock-in" in synchronization range. Here the vortex shedding frequency (f_s) gets narrower to one of the natural frequencies of the elastically mounted appendage (f_n), a nonlinear feedback loop occurs. At this point, the body's self-motion begins to control the timing of the vortex shedding. The shedding frequency "locks in" to the structural frequency ($f_s \rightarrow f_n$) instead of following the Strouhal relationship. This synchronization leads to a highly efficient transfer of energy from the fluid to the structure, resulting in large-amplitude, self-limiting vibrations.

This demonstrates that VIV is not a linear resonance problem but a self-governed and self-regulating system where the fluid and structure are coupled. The motion of the body modifies the vortex formation, which in turn limits the amplitude of the motion, typically reaching a limit-cycle oscillation with an amplitude of around one body diameter. The range of flow velocities over which lock-in occurs is known as the "lock-in range" or "synchronization region" (Zhang et al., 2015).

During lock-in, the process of vortex formation and shedding also alters the "added mass" of the cylinder. This means the effective mass of the vibrating system is not constant but changes with the fluid interaction. This can cause the resonant frequency itself to shift, which explains why the peak response may not occur at the exact location predicted based on the natural frequency in still water. This highlights that the problem is more complex than a simple mechanical vibration model and is a critical detail of the FSI feature for accurate prediction models.

4. The Consequence of Oscillation: VIV-Induced Drag Amplification

This section plays the key role on connecting the VIV phenomenon explained in previous sections to the central theme of increased drag. It critically reviews and synthesizes a wide body of experimental and computational evidence.

4.1 Evidence from experimental hydrodynamics

A series of recent experimental work conducted in towing tanks, water channels, and wind tunnels provides consistent evidence of the link between VIV and drag. These experiments show that when a cylinder vibrates (either freely or forced) at the frequencies and amplitudes characteristic of VIV, its mean drag coefficient is significantly higher than that of a stationary cylinder under the same flow conditions (Bishop & Hassan, 1964). Experiments on flexible risers have revealed that VIV may "dramatically increase the drag forces" (Huang et al., 2011; Song et al., 2017). Studies on oscillating cylinders have directly measured both lift and drag forces, confirming this increase (Riveros et al., 2014; Tofa et al., 2014).

One of the most illustrative pieces of data summarizing these findings is the plot of the mean drag coefficient (C_d) versus the reduced velocity (U_r). These plots typically show a distinct peak in the drag coefficient that coincides with the lock-in range, where the vibration amplitudes are highest (Kang et al., 2019). The drag at this peak can be more than double the stationary value (Wang et al., 2019). This provides strong evidence that VIV is not only a structural fatigue problem but also carries a significant hydrodynamic performance penalty.

The VIV response is not monolithic; it is divided into distinct branches, such as the initial, upper, and lower branches. The drag amplification is not uniform across the lock-in range. The peak in the drag coefficient typically coincides with the upper branch, where the transverse amplitudes are at their maximum. This suggests a strong correlation between the transverse vibration amplitude and the magnitude of the mean in-line drag increase (Jauvtis & Williamson, 2004). The physical mechanism is likely that the large transverse velocity component increases the effective relative velocity and angle of attack seen by the cylinder, altering the wake dynamics and increasing the form drag.

4.2 Insights from computational fluid dynamics (cfd)

CFD simulations have served as a powerful tool to corroborate and extend experimental findings. CFD enables a detailed examination of the pressure and shear stress distributions on the surface of the oscillating body, providing physical insight into the reasons for the drag increase (Tofa et al., 2014; Asyikin, 2012; Saltara, 2011). Numerical studies confirm the trend of drag amplification, with CFD results demonstrating "similar trends with experimental results" (Tofa et al., 2014). Simulations closely reproduce the characteristic peak in the the C_d vs. U_r curve observed in experiments. The role of the Reynolds number has also been investigated, with some studies indicating that the magnitude of drag amplification may diminish as the Reynolds number enters the critical regime (Yadav et al., 2019). This reveals the complex and non-linear influence of the flow regime on VIV-induced drag.

4.3 Quantitative evidence of drag amplification

The phenomenon of VIV-induced drag amplification is not merely a qualitative observation; it has been rigorously quantified across a range of experimental and computational studies. Table 4.1 compiles key findings from the literature, providing clear numerical evidence that supports the central argument of this chapter: that appendage oscillation leads to a substantial hydrodynamic penalty.

The most critical data point presented is the Drag Amplification Factor, which is the ratio of the maximum mean drag coefficient of the oscillating body ($C_{d,max}$) to the drag coefficient of the same body in a stationary condition ($C_{d,0}$). An examination of the table reveals that this factor is consistently and significantly greater than one. For instance, CFD simulations by Yadav et al. (2019) indicated a drag amplification factor of 3.92, while combined experimental and computational work by Tofa et al. (2014) found the factor to be approximately 3.05. Even in studies focused on more complex systems like flexible risers, the amplification factor was observed to be greater than 1.70 (Song et al., 2017).

Furthermore, the table illustrates a strong correlation between the vibration amplitude (A/D) and the magnitude of drag increase, a concept introduced in Section 4.1. The highest amplification factors are often reported in studies where the transverse vibration amplitude approaches or exceeds one characteristic diameter of the body, as seen in the work by Tofa et al. (2014). This quantitative data, gathered across different methodologies (from physical experiments to various CFD approaches like RANS and LES) and a wide span of Reynolds numbers, provides robust evidence. It underscores the conclusion that the increase in mean drag during VIV is a powerful and repeatable physical phenomenon, making it a critical consideration for naval architects in predicting vessel performance.

Table 4.1. Compilation of Reported Drag Amplification Factors from Key VIV Studies.

Study	Methodology	Reynolds Number Range	Max. Amplitude (A/D)	Drag Amplification Factor $(C_{d,max}/C_{d,0})$
Tofa et al. (2014)	Experimental – Free Vibration / CFD (LES)	$< 1.1\times10^5$	~ 1.19	~ 3.05
Yadav et al. (2019)	CFD (RANS)	$100 – 10^6$	Not Specified	3.92
Franzini et al. (2012)	Experimental – Free Vibration	3000 – 13000	~ 1.0	~ 3.43
Song et al. (2017)	Experimental – Free Vibration (Flexible Riser)	Up to 2.2×10^5	> 0.75	> 1.70
Wang et al. (2019)	CFD (RANS)	8000 – 56000	~ 0.6 (suppressed)	~ 3.00

5. Conclusion: Towards a Dynamic Understanding of Appendage Drag

This final section synthesizes the principal findings of the report and restate the central thesis in light of the evidence presented. It will advocate for a paradigm shift in the understanding of appendage drag, moving from a purely static perspective to a more holistic, dynamic framework that incorporates the complex effects of fluid-structure interaction.

5.1 Synthesizing the evidence

This chapter presents a narrative that establishes the economic imperative for drag reduction, defines the static drag of appendages, elucidates the physics of VIV, and critically evaluates the evidence for VIV-induced drag amplification. The bulk of the literature indicates a significant increase in drag, confirming that the dynamic motion of appendages is a critical factor in overall vessel performance.

5.2 The inadequacy of static analysis

The primary conclusion is that a simple, static analysis of appendage drag based on wetted surface area and form factors is inadequate for accurate performance prediction and structural design. The dynamic response of appendages to the flow is a critical factor that must be considered. The fatigue damage caused by VIV is undisputed and necessitates a dynamic analysis.

5.3 Future directions: research and design

The chapter concludes by encouraging future research aimed at further refining the prediction of VIV and its effects. This will necessitate more high-fidelity, free-vibration experiments and advanced, fully-coupled CFD simulations that can accurately capture the fluid-structure interaction across various flow regimes and appendage geometries. For naval architects and designers, the key takeaway is a call for greater awareness of the potential for VIV on all hull appendages, not just on traditional offshore structures. Early-stage design analysis should incorporate screening for potential lock-in conditions.

Ultimately, this report reinforces its title: oscillating appendages are indeed a hidden, complex, and critical source of drag in naval architecture. Only by understanding their dynamic behavior can we design the next generation of more efficient and reliable vessels.

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