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Faculty of TRANSPORT
TRANSPORT DOCTORAL SCHOOL

SUMMARY DOCTORAL THESIS

Sustainable maritime transport through optimization of consumption

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1. INTRODUCTION

1.1 Timeliness and relevance of the PhD thesis

The globalisation of the world economy has generated large quantities of goods that needed to be transported and has boosted maritime transport over the last twenty years. The advantage of maritime transport is not based on the speed of transport, but on the huge transport capacity.

Shipping is expected to expand by 2.4% in 2023 and maintain a growth rate of over 2% between 2024 and 2028. However, the sector faces sustainability hurdles, including emissions, pollution, the impact of climate change and stringent regulations.

From the scientific work reviewed during the study, several factors will influence the trajectory of shipping.The sector is sensitive to the impact of climate change and contributes to it through its emissions. The sector faces regulatory challenges, cumbersome diffusion, changing rules and geopolitical uncertainties. Rising costs of regulation and investment in technology are another challenge.

1.2 Objectives

In view of the need for sustainable development of maritime transport, the PhD thesis entitled *" Sustainable maritime transport through optimization of consumption"* takes a holistic approach to analyze the drivers of *consumption* in the varied context of sustainability. Thus, sustainability integrates multiple components that can be individually optimised, most of which are reflected in different forms of consumption.

With the aspiration to contribute to the diversification of methods for the sustainable development of maritime transport, I have set the following objectives for this paper:

- Review current research on sustainability and identify key components that support its growth,
- Deepen the understanding of the role of regulatory entities in the shipping industry and the measures adopted in favour of sustainability,
- Identification of consumption patterns and choice of optimisation directions,
- Carry out a detailed study on the Romanian Black Sea marinas, evaluating operational procedures, identifying shortcomings and possibilities for optimisation,
- Case study on the algorithm for optimizing the berthing of boats , in the context of planning the activity of tourist ports,

- Exploring the potential of the backtracking algorithm in optimizing the speed of a ship intended to supply the maritime platforms in the Romanian Black Sea area,
- Energetic balance improvements of a passenger ship through the optimization ol lighting system control

1.3 State of art

Shipping is the most cost-effective and efficient way of transporting large volumes of goods and plays an important role in driving the global economy.

However, even if it is efficient, it faces difficulties in terms of sustainability, through its environmental impact, resource use and emissions. Dependence on fossil fuels has significant environmental consequences through greenhouse gas emissions and pollutant emissions. These observations highlight the need to implement measures to steer the maritime industry towards a more sustainable path, thereby reducing negative environmental impacts and ensuring long-term viability.

According to the United Nations Conference on Trade and Development (UNCTAD, 2022), the volume of shipments has increased significantly in 2021, reaching a total of 11 billion tonnes (Figure 1).

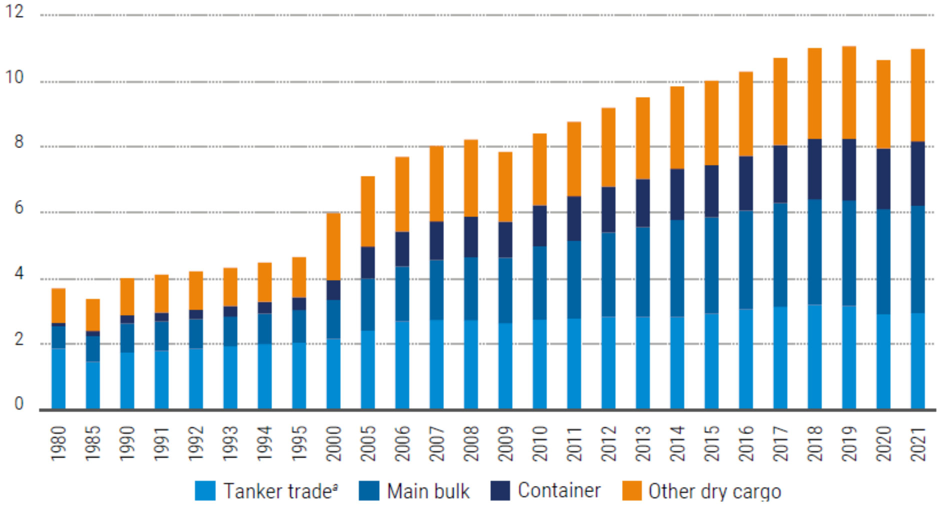


Figure 1. International seaborne trade by type of cargo annually, in billions of tonnes loaded (Source: UNCTAD, 2022)

The rapid growth of the maritime sector and its operational nature bring a substantial environmental footprint. Despite the fact that shipping currently accounts for 2-3% of global CO_2 emissions, projections suggest that if no action is taken, it could account for up to 17% of total annual CO_2 emissions in 2050 (ITF Transport Outlook, 2019).

Shipping involves various costs, which are in fact a form of **consumption** when, for example, they relate to resource use, labour costs or operational costs. The relationship between shipping sustainability and consumption extends beyond the environmental conservation dimensions, as it incorporates both social and economic aspects.

From a social point of view, the adoption of sustainable consumption practices in the shipping sector has the potential to improve working conditions and the general welfare of seafarers. Consumers can help promote ethical and socially responsible shipping operations by supporting companies that prioritise fair labour practices, decent wages and safe working environments. These factors have the potential to enhance the welfare of crew members, mitigate labour exploitation and promote respect for international labour standards in the maritime sector.

Fostering sustainability within the shipping industry has the potential to stimulate innovation and contribute positively to global economic expansion. Promoting sustainable transport methods can stimulate product demand in the market, driving companies to invest in research and innovation to develop more environmentally friendly technologies.

Sustainability challenges and opportunities in the maritime sector have been a focus of scientific research in the field.

In this paper we have selected for analysis studies necessary to achieve the fence-building objectives that underline the urgent need for maritime transport to continuously evolve towards sustainability:

- Benamara et al. (2019) highlight the role of shipping in achieving sustainable development, highlighting its many facets, from energy efficiency to rules-based systems.
- Koilo (2019) discusses the sustainability challenges of the maritime industry, including environmental and socio-economic impacts.
- Singh et al. (2020) highlight efforts to modernise shipping by updating the legal and infrastructure framework.
- Wang et al. (2020) analysed the sustainability reports of major maritime players, proposing a framework that describes the industry's evolving commitment to sustainability. Their findings highlight the varied motives and sustainability efforts in the maritime industry.
- Papandreou et al. (2021) emphasise the need for the maritime sector to reduce sulphur and CO_2 , presenting existing sustainability initiatives as models for wider industry adoption.
- The role of marine spatial planning (MSP) in enhancing maritime social sustainability is gaining ground. While traditionally focusing on governance and environmental issues, recent studies, such as those by Saunders et al. (2019) and Frederiksen et al. (2021), highlight the need to incorporate elements of social sustainability, including democratic decision-making and socio-cultural values.
- Karakasnaki et al. (2023) provide an empirical perspective on social responsibility, identifying five basic components: physical, functional, health, culture and communication. Their findings suggest that ship flags do influence seafarers' perceptions of these components, providing policy and managerial insights for improving seafarers' well-being and sustainability.
- De Kat and Mouawad (2019) delve into sustainable shipping through technological interventions, from air lubrication to optimized ship design.
- Gourdon (2019) examines ship recycling, revealing its negative environmental impacts and implications for species diversity and human health.
- Psaraftis et al. (2019) compare the effectiveness of speed limits and bunker taxes in reducing greenhouse gas emissions, concluding that although speed limits enjoy some support, they are less effective than bunker taxes.

- Of the three pillars of sustainability, research has predominantly focused on the environmental element, particularly in relation to marine vessels and port infrastructure (Lee et al. ,2019)
- Ukić et al. (2021) rank the impact of boating activities on the environment, showing that shipping is an area of active research over other sectors.

It is noted that the number of scientific publications over the last 5 years dealing with the environmental impacts of maritime transport is increasing. This can be illustrated by searching the Web of Science Core Collection and centralising the data.

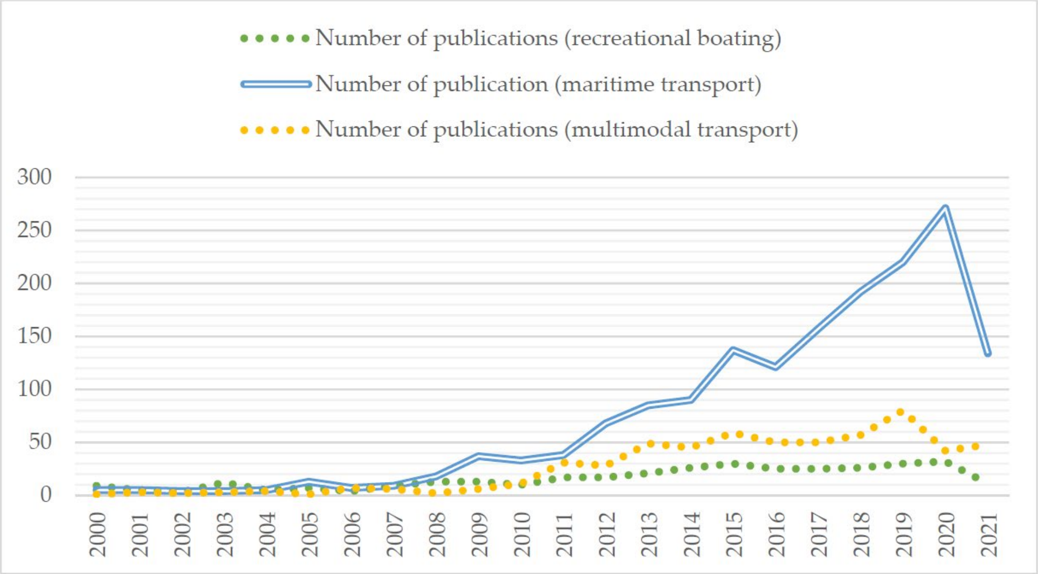


Figure 2. Number of research studies involving maritime transport compared to recreational boating and multimodal transport. (Source: Ukić et al., 2021)

Therefore, the approach to sustainability must be holistic because each element of improvement can negatively affect other aspects. Research can lead to the choice of the most effective optimisation methods that will bring solid future benefits.

2. SUSTAINABLE MARITIME TRANSPORT

2.1 IMO`s role

The International Maritime Organization (IMO) is a specialized agency of the United Nations charged with regulating world shipping that plays an important role in regulating and promoting safe and sustainable shipping practices worldwide.

The IMO regulates all technical aspects of international shipping through 53 treaties, backed up by hundreds of codes and guidelines, covering the entire life cycle of merchant ships from delivery to dismantling.

The three main categories of conventions adopted by the IMO are:

1. Maritime Safety Conventions (MSC) adopted by the IMO to promote the safety of life at sea and to protect the marine environment through standards, rules and regulations on the design, construction, equipment, manning and operation of merchant ships.
2. Marine Pollution Prevention Conventions are international treaties established to prevent and reduce marine pollution.
3. The Conventions on maritime liability and compensation have the essential role of establishing a comprehensive legal framework for establishing liability and ensuring adequate compensation in the event of maritime accidents, in particular oil pollution damage.

The most recent session of the Marine Environment Protection Committee (MEPC) in 2023, known as MEPC 80, led to the revision of the existing greenhouse gas (GHG) policy. This updated strategy presents a highly ambitious approach to mitigating GHG emissions from the international shipping sector. The IMO has adopted an ambitious strategy to decarbonise international shipping by 2050 through improved energy efficiency, the adoption of zero emission fuels and the setting of incremental targets.

Table 1: Updated GHG reduction strategy, IMO MEPC 80 (2023)

Ambition levels	Description	Target reduction	Deadline
1	Reviewing energy efficiency design requirements for ships and improving energy efficiency for new ships	-	-
2	Reducing CO_2 emissions per transport unit	minimum 40% compared to 2008	2030
3	Increasing the use of new technologies, zero or near-zero GHG emission fuels and energy	at least 5% (with a target of 10%) of energy used in maritime transport	2030
4	GHG emission peaks	net zero greenhouse gas emissions	2050
5	Reducing total annual GHG emissions	at least 20% compared to 2008 (target is 30%)	2030
6	Reducing total annual GHG emissions	minimum 70% compared to 2008 (target 80%)	2040

To achieve these objectives, the Organization will take the following measures:

1. IMO will work to improve energy efficiency and reduce the carbon intensity of shipping.
2. IMO will promote the use of zero emission fuels such as hydrogen and ammonia, as well as other alternative fuels.
3. IMO will encourage the development and deployment of new technologies such as carbon capture and storage and wind assisted propulsion.
4. The IMO will promote the use of operational measures such as speed reduction and improved voyage planning to reduce emissions.

5. The IMO will work with governments, industry and other stakeholders to support research and development of new technologies and fuels.
6. The IMO will continue to monitor and evaluate the effectiveness of its policies and measures to reduce GHG emissions from shipping.

These measures are part of a step-by-step strategy to achieve ambitious targets for reducing greenhouse gas emissions from shipping. The industry's transition to zero emission fuels and technologies will require significant investment and collaboration between governments, industry and other stakeholders.

2.2 Sustainable shipping framework

The structure of susteinability has been proposed by many researchers, the common and accepted theme is based on three pillars. The three pillars are in turn made up of specific activities that intersect and together contribute to building the concept of sustainability. The pillars represent the economic side, the environmental impact and the social side, between which a balance must be struck.

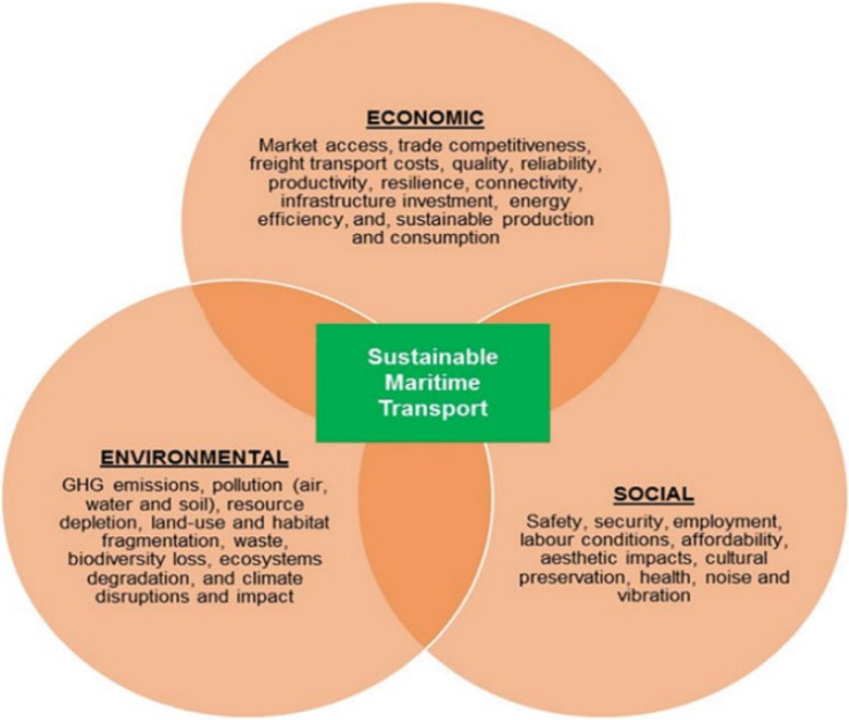


Figure 3. The concept of sustainability in the maritime industry (Source: Benamara et al. 2019)

The literature review showed that research has predominantly focused on the environmental element, particularly in relation to marine vessels and port infrastructure (Lee et al. ,2019). In order to provide a comprehensive understanding of the concept of sustainability in shipping, it is imperative to examine all three fundamental pillars of sustainability, namely environmental, social and economic aspects.

The environmental dimension focuses primarily on mitigating the environmental impact of the industrial sector, including reducing greenhouse gas emissions, preventing marine pollution and preserving biodiversity.

The social dimension encompasses the responsibility to protect the welfare and safety of seafarers, to advocate for fair labour practices and to actively engage with local communities affected by maritime operations.

The economic pillar places a strong emphasis on the need for companies to be profitable and efficient, while taking into account the long-term viability of the sector. It is possible to establish a complete picture of the sustainability of shipping by investigating these interrelated characteristics.

To assess the environmental impact, the IMO has commissioned studies to quantify emissions from shipping.To date, four IMO studies on greenhouse gases have been published.The quantified results show an increase of CO_2 emissions from ships.

Table 2. IMO studies (Source:Author)

Year	Resolution/Document	Reference year	Resulting quantities
2000	First IMO study on greenhouse gas emissions	1996	1.8% of global anthropogenic CO_2
2009	Second IMO study on greenhouse gas emissions	2007	880 million tonnes (2.7% of total global anthropogenic CO_2)
2014	Third IMO study on greenhouse gas emissions	2012	796 million tonnes (2.2% of total global anthropogenic CO_2)
2020	Fourth IMO study on greenhouse gas emissions	2018	1076 million tonnes (2.89% of total global anthropogenic CO_2)

International shipping accounted for 2.7-3% of global anthropogenic CO_2 emissions between 2012 and 2018, mainly driven by emissions from commercial shipping.

Even though waterborne transport produces the lowest emissions, unfortunately the CO_2 emissions of the world fleet are going in the wrong direction, increasing year after year (figure 4). This trend is driving the overall environmental impact of the maritime industry in the wrong direction, with a 24% increase between 2012 and 2022, due to several factors.

Increases in cargo volumes and vessel size without commensurate increases in efficiency, increased vessel speed and utilisation, limitations in technical and operational measures, minimal transition to low-carbon fuels and the ageing of the world fleet have all contributed to this situation.

Another reason is economic instability, with companies reluctant to build new ships and invest heavily in technological development. The uncertainty of the global supply chain attracts reserved action from investors.

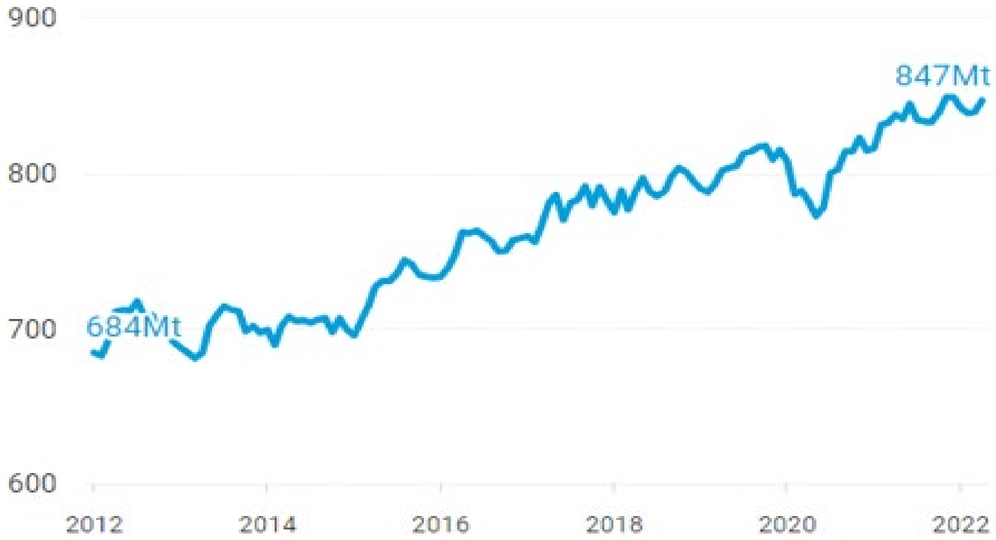


Figure 4. CO_2 emissions (Source: UNCTAD based on Marine Benchmark data, 2023)

Implementing measures to control CO_2 emissions and finding ways to make the fleet more efficient are essential for a sustainable future development of shipping.Energy efficiency improvements, lower consumption and operational optimisations have so far proved insufficient in the face of the overall growth of the sector.

It is urgently necessary to quickly find and implement solutions to reduce emissions from shipping. In my opinion, these solutions should be tailored on a case-by-case basis. Even if there are strong companies that benefit from funding and can access state-of-the-art technologies, there are many others that do not have sufficient capacity to build new ships or upgrade existing ones. That is why I believe that implementing alternative solutions such as algorithms or mathematical models can be cost-effective to implement and help preserve the marine environment.

3. THE ROLE OF CONSUMPTION IN THE MARITIME INDUSTRY

While the operation of a ship primarily involves fuel and energy consumption, it is important to note that there are other forms of consumption. The objective of this chapter is to identify types of consumption in shipping. Knowing the characteristics of these consumptions is the foundation for implementing optimisation methods and for accurate and efficient evaluation of results. Thus, through a thorough understanding of consumption in maritime transport, the path towards more efficient and sustainable solutions in this sector can be traced.

Defining sustainability as a functional linking of inputs and outputs can provide a quantitative way of approaching and measuring :

$$S = \frac{\sum_{j=1}^{m} Y_j}{\sum_{j=1}^{n} X_i} \tag{1}$$

where:
S stands for sustainability of resource use,
X_i where i=1,2...n, represent the utilities in the Von Neumann-Morgenstern sense (which are additive) of all types of inputs (e.g. resource type),
Y_j where j=1,2...n, represent the utilities (which are additive) in the Von Neumann-Morgenstern sense of all types of outputs (e.g. emissions type).

The ratio of outputs to inputs serves as a simplified representation of sustainability. The more outputs a system can produce with fewer inputs, the more sustainable and efficient it is. If, however, the outputs are harmful emissions, then the expectation is that they will decrease.

While the objective function provides clear direction, real-world sustainability implies constraints. These may be related to resource availability, environmental regulations or social considerations. Inputs may represent resources such as raw materials, energy, labour or capital while outputs may represent products, services or value generated by the system.

The formulation shown is a single-objective function, but sustainability often requires balancing multiple objectives. For example, a company might want to maximise both profit and environmental friendliness, which can sometimes be at odds with each other. Factors such as the long-term sustainability of resources, social impacts (e.g. fair labour practices) and environmental externalities (e.g. pollution) may not be captured by the production/input ratio alone.

Sustainability is not just about resource efficiency. Perceptions, expectations and alignment of stakeholder values play a crucial role. For example, a company may have a high output to input ratio, but may be perceived as unsustainable because of its negative impact on the community. Additional variables can also be introduced to account for waste, by-products or other unintended consequences of a process. This would provide a more comprehensive view of sustainability.

Table 3 provides an overview of the various consumption patterns in the shipping industry, highlighting both economic relevance and environmental impact. For shipping to be considered truly sustainable, it is essential to try to achieve maximum efficiency with the minimum possible input.

Table 3. Examples of consumption (Source: Author)

Categories	Features	Impact
Energy consumption	Shipping consumed over 250 million tonnes of fuel in 2018. Reducing fuel consumption through energy efficiency is crucial for cost and decarbonisation	Can lead to significant economic losses and potential supply chain disruptions **Do not admit stock shortage**
Materials and resources	The construction, maintenance and operation of ships requires large quantities of steel, aluminium, copper, lubricants, paints and other raw materials. Adopting circular economy approaches to material reuse can increase sustainability	May delay essential repairs or construction of new vessels, leading to increased costs and operational inefficiencies **Partial stock-outs are accepted.**
Water consumption	Water is vital on board ships. Improving efficiency and production can help optimise	A zero reserve scenario would be catastrophic

	the use of fresh water	**Do not admit stock shortage**
Food consumption	Crew and passengers on ships consume large quantities of supplies. Avoiding waste and managing supplies and supply chains sustainably can reduce the environmental footprint.	May pose direct health risks to crew and passengers **Partial, stock shortage accepted**
Consumerism and waste	Cruise ships generate large volumes of consumer waste. Passengers also contribute significantly to energy and water consumption on board. Promoting behavioural change is important.	In some cases, they can lead to loss of revenue, such as passenger transport.
Ecosystem services	Dredging, underwater noise pollution, waste dumping and port infrastructure developments consume the natural services of coastal ecosystems.	Excessive consumption of ecosystem services could lead to long-term ecological damage that could be irreversible.

3.1 Romanian marinas sustainability factors, case study

A marina or tourist port, also called a "marina", is a type of harbour used mainly by boat crafts and is associated with nautical tourism, an integral part of maritime transport, playing an important role locally.

In the literature, for the Black Sea littoral, there is no clear data on the extent of nautical tourism development, but it is recognized that it is developing and requires analysis to show the extent and impact of these activities (Luković, 2012). The aim of this chapter is to study the impact of the activities of these ports and the sustainable practices used.

Research is needed, given the current lack of comprehensive data on marina practices in Romania and the overall scale of the industry.

An additional argument for the usefulness of this research arises because there is an initiative in line with the national strategic development plan to modernise and develop new tourist ports on the Black Sea coast (CJC,2022).

Conducting a thorough assessment of the current operations of existing Romanian marinas, evaluating their environmental impact and identifying areas for improvement can guide the sustainable development of new marinas.

Historically, marinas have received less attention from researchers than commercial marinas, the latter often including marinas in a particular area of operation. However, marinas are becoming increasingly important due to the positive economic impact generated by the recreational boating sector, where the necessary facilities exist.

The existence of marinas should not be ignored in the discussion on the sustainability of maritime transport as they too can contribute to maritime pollution in their areas of operation and affect both climate change and the health of coastal residents.Table 4 presents several ways in which marinas integrate into the shipping network.

Table 4. Role of marinas in the overall MTS (Source: Author)

Role	Description
Transport	Act as hubs for local water transport in some coastal and island communities, including services such as ferries and water taxis
Facilities for coastal navigation	Provides moorings and servicing for recreational boats such as yachts, sailboats and personal watercraft Provides infrastructure for operations such as fueling, boat maintenance and waste disposal
Tourism and leisure industry	Located in tourist destinations, they contribute to the local economy by serving tourists who rent boats for recreation. They can also accommodate tour boats for sightseeing
Fishing industry	Serve as mooring ports for small-scale commercial fishing vessels Provides services such as ice, bait, fuel, boat repairs and a place to unload catch
Environmental protection	Engage in activities to promote clean boating practices Manages waste disposal to prevent pollution and sometimes participates in habitat restoration projects
Competitions and regattas	They host yachting competitions involving fast sailing boats.

I have carried out an analysis study on the level of development of tourist ports in the Romanian Black Sea coastal area and their implications for the sustainable provision of quality leisure transport. The results were published in the MDPI journal, *Sustainability.15(10):7979, (2023).*In Romania, there are about 11300 boats and several small inland tourist ports, as well as four developed ports on the Black Sea (Publications Office of the European Union, 2016).

The marinas studied are Tomis Port (Constanța), Belona (Eforie Nord), Mangalia and Limanu (figure 5).

Figure 5. Studied marinas (Source:Author)

The characteristics of the marinas studied such as level of facilities, location, connection to the sea, pontoon/dock facilities, types of moorings are presented in Table 5.

Table 5. Characteristics of the Romanian selected marina`s (Source: Author)

PORT Feature	Tomis Constanta	Belona Eforie Nord	Mangalia	Limanu Port
Equipment level	Standard, with basic utilities, but surrounded by restaurants and private hotels.	Standard with basic utilities and restaurant	Standard with basic utilities	Semi-advanced with leisure facilities: hotel, restaurant and bar, sports ground, conference room.
Location	Urban	Near the beach with road access	Urban	Remote with road access
Entry	Port entrance	Basin entrance	Port entrance	Entering through the canal
Types of moorings	Stern to pontoon with bow anchored to buoy or near pontoon	Aft to the quay, bow anchored to the anchor or buoy	Along the quays, double berths	Stern to pontoon, anchored, buoys

3.2 Research framework

Analyzing similar studies in the field of coastal shipping in other regions and considering that no study in the literature addresses sustainable practices applied by marinas in Romania, a qualitative/quantitative approach was chosen.

The analysis framework prepared is shown in Figure 6. The data used were data collected from a questionnaire, or from direct discussions with representatives of the four marinas studied and local maritime administrations, or from public data on this activity.

The questionnaire was proposed in order to obtain information covering the basic principles of sustainable development and addressed:

- Waste management policies;
- Use of renewable energy sources and energy efficient equipment;
- Local impact;
- Workforce and human resources;
- Relevant industry certifications.

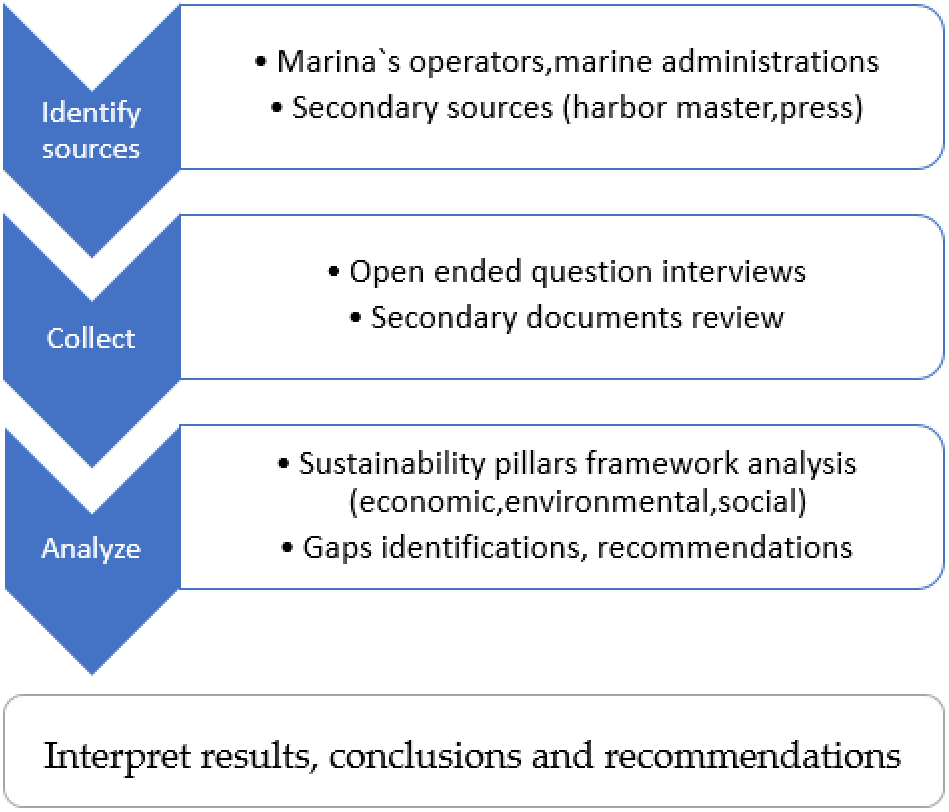


Figure 6. Research framework (Source: Author)

Over the last 20 years, there has been a growth rate in nautical tourism in Romania. As shown in Figure 7, we can see that from 2014 to 2019, there has been a 65% increase in the number of boats moored in the southern region in Mangalia and Limanu marinas, and this represents a positive trend. Even during the pandemic, many chose personal watercraft over room accommodation or other types of tourism.

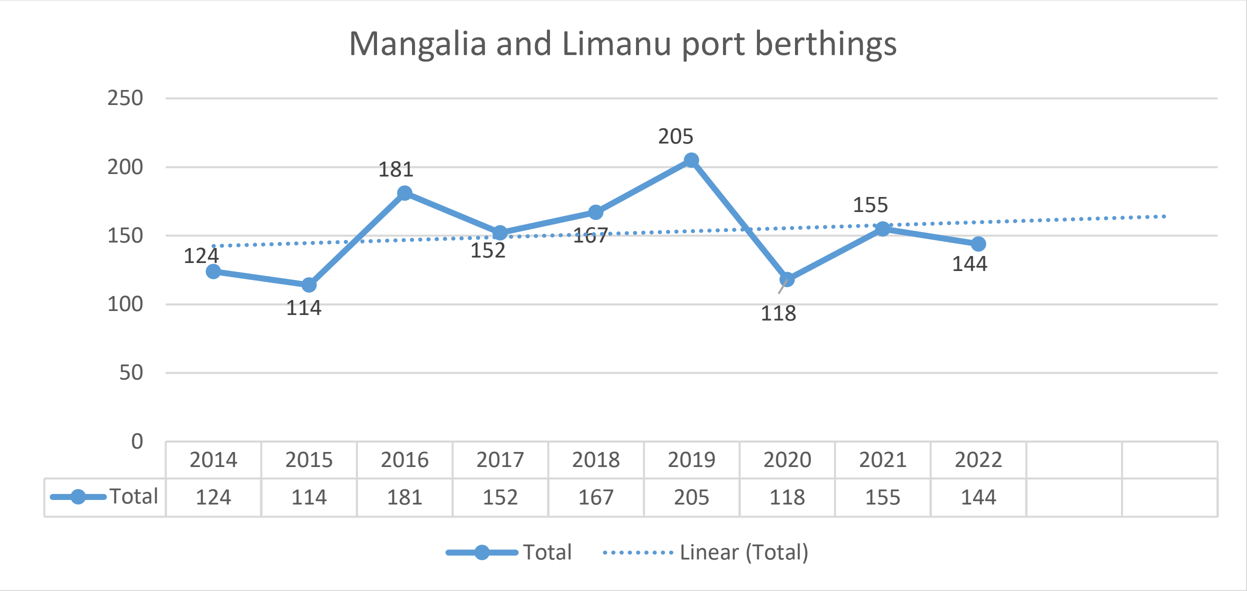


Figure 7. Limanu and Mangalia boat traffic (Source: Author)

A comprehensive set of characteristics was used to assess the performance of the ports, taking into account the three pillars of sustainability. Data collection methods were: direct observation, questionnaire analysis, data collection from the press as well as from local government public sources. For the assessment of the number of boats, data from the Mangalia Harbour Master's Office and where possible from online sources monitoring the AIS systems of the boats were used.

Recreational boating is part of the overall maritime transport system and can be assessed according to the sustainability principle defined in Chapter 2. This principle must be adapted to the specific nature of marinas. Thus we have generated a list of relevant elements specific to the activity studied chosen on the basis of the three general principles of sustainability, economic, environmental and social (figure 8).

Economic

- Berthing spots (B)
- Usable water surface area (W)
- W/B ratio
- Maximum boat length
- Management
- Type

Environment

- Water supply
- Fuel supply
- Use of RES
- Electric supply—shore power
- Collecting of garbage
- Waste oil and ballast water
- disposal system
- Pollution prevention equipment
- Desalination, rain recovery
- Boat maintenance services
- Green surfaces
- ISO14001
- Blue Flag

Social

- Wi-Fi Internet connection
- Recreational facilities
- Hosting trainings, events, regattas
- Urban
- Road access, parking
- Mobile app access
- CCTV—security cameras
- Boat ramps or cranes
- Review score , based on Google.com

Figure 8. Durability characteristic (Source: Author)

In terms of usable water area, Mangalia has the largest area with 41% (17 ha) of the total usable water area in all four locations, followed by Tomis with 14% (6 ha), Limanu with 9% (3 ha) and Eforie Belona with 2% (1 ha), as shown in Table 6.

The maximum length allowed for boats also varies from location to location, with 24m allowed in Limanu and Tomis, 18m allowed in Mangalia and 12m allowed in Eforie Belona (Table 6).

Table 6. Economic characteristics (Source:Author)

Description	**Tomis**	**Eforie Belona**	**LifeHarbour Limanu**	**Mangalia**
Number of places (B)	300	60	140	146
Aquarium surface area (W)	60 ha	10 ha	30 ha	170 ha
W/B ratio	200	167	214	1164
Maximum permitted length	24 m	12 m	24 m	18 m
Management	PPr	PPr	Pr	P

In terms of management, Eforie Belona and Tomis are managed by a public-private partnership (PPr), representing 50% of the sites, while Limanu and Mangalia are managed by private (P) and public (Pr) management respectively. This could indicate that Eforie, Limanu and Tomis could be more focused on providing quality services to their customers. In contrast, Mangalia has a different type of management, which may have different priorities and focus on different aspects of marina operation.

Table 7. Environmental facilities (Source:Author)

Description	**Tomis**	**Eforie Belona**	**LifeHarbour Limanu**	**Mangalia**
Water sources	Y	Y	Y	Y
Fuel facilities	N	N	N	N
Renewable sources	N	N	N	N
Bad electrical connection	Y	Y	Y	Y
Garbage collection	Y	Y	Y	Y
Oil collection, ballast	N	Y	Y	N
MARPOL equipment	N	N	Y	Y
Desalination, rain collection	N	N	N	N
Repairs facilities	Y	N	Y	N
Nature, green areas	Y	N	Y	N
ISO14001	N	N	N	N
Blue Flag	N	N	N	N

Y-available; N-unavailable

Water and shore power are available at all locations. All locations have access to shore power for electricity supplied by the local electricity company. Waste and rubbish, where collected, is then delivered to local recycling companies. The use of renewable energy sources (RES) and desalination and rainwater harvesting systems are not available at any location. None of the marinas surveyed have approved fuel supply facilities (Table 7).

Mangalia and LifeHarbour Limanu have waste oil and ballast water disposal systems and pollution prevention equipment. Tomis and LifeHarbour Limanu offer boat maintenance services and have green spaces. At the time of the survey, none of the sites had ISO14001 or Blue Flag environmental certifications.

Based on this data, it can be concluded that the availability of certain services varies from location to location, and some locations have a more comprehensive set of services than others. Lack of fuel supply, use of renewable energy sources and environmental certifications may be areas for improvement in all locations. The presence of waste disposal and pollution prevention equipment is important for safety and environmental protection. The availability of boat maintenance services and green spaces can be a factor in attracting boaters to certain locations.

Table 8. Social characteristics (Source: Author)

Description	Tomis	Eforie Belona	LifeHarbour Limanu	Mangalia
Internet connection,WiFi	N	Y	Y	N
Recreational places	Y	Y	Y	N
Events organisation	Y	Y	Y	Y
Urban	N	Y	N	Y
Street access, parking	Y	Y	Y	Y
Mobile app	N	N	N	N
CCTV	N	Y	Y	N
Access ramp, crane	Y	Y	Y	N
Reviews *	4.5	4.3	4.6	4.7

* Data collected by Google; Y-Available; N- Unavailable

As a result of the research, a **SWOT** analysis was carried out on the activity of marinas and the development of nautical tourism.

Table 9. SWOT ANALYSIS (Source: Author)

Strengths	Weaknesses
High potential due to increased interest in water tourism Natural attractions Proximity to developed and safe urban areas A rich cultural and historical heritage Accommodation and catering facilities Good infrastructure Accessible from the Black Sea and Danube Sailing schools and event organisations	Limited accommodation capacity for large vessels Lack of skilled workers Insufficient information to tourists about offers Lack of a clear and defined strategy for the development of nautical tourism Lack of certifications Missing IT development such as booking apps, real-time data
Opportunities	**Threats**
Untapped potential Proximity to the Danube Delta and inland waterways Involvement of travel agencies Hosting international regattas Development of ancillary services (boat repairs, equipment sales, maintenance) Organising themed excursions, dolphin watching, scuba diving	Not enough awareness of the importance of water tourism Impact of political factors, corruption and bureaucracy Impact of potential health crises or political instability Proximity to conflict zones in the Black Sea (Ukraine) Lack of a clear development strategy

The research highlights gaps in sustainable marina development policy in Romania, providing key recommendations to improve their environmental, social and economic sustainability.

From the study the following can be deduced:

- From an environmental point of view, it is vital that marinas adopt strict policies to combat pollution and protect the coastal ecosystem, with potential measures including waste management systems, adoption of renewable energy and green building guidelines.
- On the social side, the growing interest in maritime recreation suggests that marina development can boost tourism, benefiting local economies and improving the overall quality of life.
- From an economic point of view, marinas have significant potential to attract investment, stimulate related industries and generate jobs.
- This information is intended to guide the intensive and extensive development of leisure tourism as well as the sustainable development of the Romanian Black Sea coast, harmonising its growth with the unique geographical attributes of the region.

4 . OPTIMIZATION MODELS

Operational Research (OR) had as its starting point the very shipping problem (Koopmans' problem) of maximising the shipping capacity of the Allied fleet in order to reduce the time ships were exposed to the danger posed by German U-boats in World War II. The connection of this area of mathematics with transport is also given by the development of the classical transport problem as a particular case of the linear programming problem. Furthermore, quantitative tools and techniques have been developed for modelling complex transport systems with the aim of optimising their performance.

The models allow the analysis of different scenarios and alternatives to provide data-driven information. Maritime operations involve substantial uncertainties due to weather conditions, fluctuating demand, supply chain dynamics, price fluctuations and resource availability.

The use of optimisation algorithms in the maritime industry is more relevant today than ever before. This is primarily due to the continuous ageing of the fleet, which makes it difficult to adhere to current environmental policies by adopting new technologies for the current fleet. There is also a real bottleneck in the construction of new ships, as their costs are huge and pay off slowly, so they have to be used for a long time and research into new energy sources is ongoing.

Based on the United Nations Conference on Trade and Development's 2022 review, in 2021 the average age of the world fleet of ships, was:

- 21 years for container ships,
- 27 years for bulk carriers and
- 30 years for oil tankers.

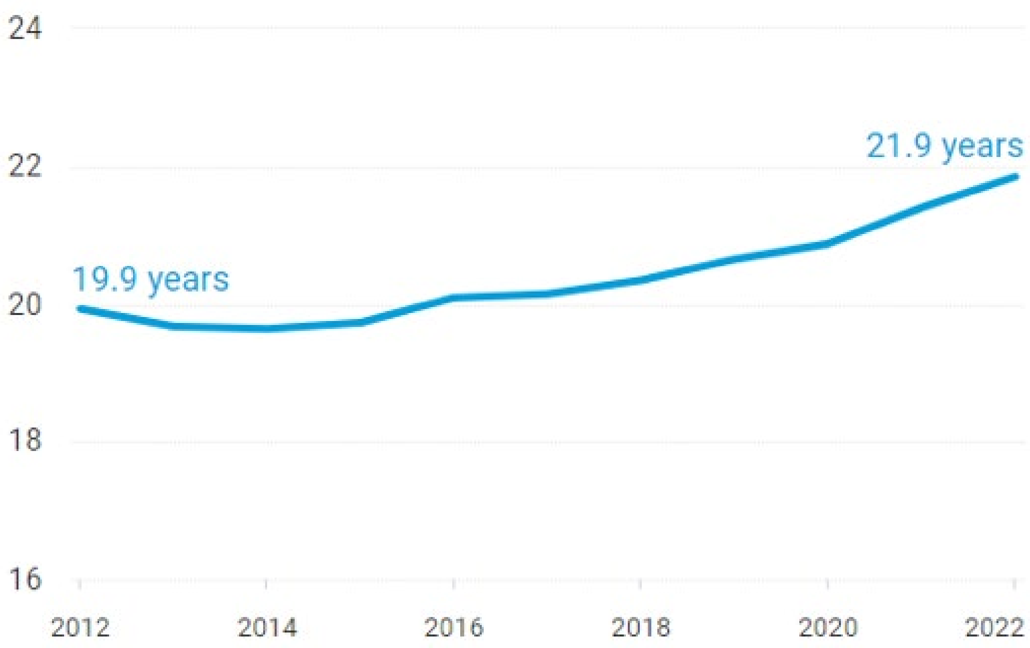


Figure 9. Average age of the world fleet (Source: UNCTAD,2022)

4.1 Berthing allocation algorithm, application

The case study presented in chapter three identified some of the problems faced by marina administrations, and port congestion in peak season is one problem. Romanian marinas do not have a specialised berthing programme or an interface with other software platforms to program berthing times. In reality, boats have to contact the marina in advance to see if they can berth there. While this approach can be useful during periods of low activity, in summer, however, when there is congestion, boat owners can let the marina know how many berth days they need and the marina can allocate berths efficiently based on berth requests so that there are no waiting times due to unavailability of a berth. In contrast to the way specialised berths for the transport of goods or people are organised with strict demarcation, boats anchor sternways (backwards) rather than lengthways.

For this reason the facility offered to them is called continuous berth. Another peculiarity is the small size of the aquarium (harbour basin), which does not allow to provide an area to wait for the entrance to the berth and therefore to connect to the harbour facilities. These reasons required the adaptation of the existing algorithms for continuous berth to the peculiarities of marinas and thus we developed a model for coordinating the arrival of boats in a marina without waiting times for reception in the harbour.

The scenario is developed for the scheduling in 15 days (360 hours) of ten yachts at quay no.1 of the marina Constanta - Tomis. Their sizes and the number of days they will be at the quay are transmitted to the boat operator, so they are known. The length of the quay is 30 m. The objective is to optimise the scheduling of the entry of vessels in order to avoid waiting time at the entrance to the port and it is carried out in two stages (Table 10).

Table 10. Structure of the allocation algorithm (Source: Author)

STAGE	RESOLUTION	ALGORITHM	REMARKS
1	Finding arrival times so that there is no waiting for anchorage	Dynamic Continuous Allocation Algorithm (BAP)	Version adapted by the author
2	Identifying the possible location of a craft in the space-time diagram	Greedy Randomized Adaptive Search Procedure (GRASP)	Version adapted by the author

The mathematical formulation of the problem according to Lee, et al. (2010), is to minimize the objective function :

$$\mathrm{F} = \sum_{i=1}^{N} w_i * (c_i - a_i) \tag{2}$$

with the restrictions :

$$\begin{cases}
u_j - u_i - p_i - (\sigma_{ij} - 1) * T \geq 0 & \forall\, 1 \leq i,j \leq N, i \neq j & (3)\\
v_j - v_i - s_i - (\sigma_{ij} - 1) * S \geq 0 & \forall\, 1 \leq i,j \leq N, i \neq j & (4)\\
\sigma_{ij} + \sigma_{ji} + \delta_{ij} + \delta_{ji} \geq 1 & \forall\, 1 \leq i,j \leq N, i \neq j & (5)\\
\sigma_{ij} + \sigma_{ji} \leq 1 & \forall\, 1 \leq i,j \leq N, i \neq j & (6)\\
\delta_{ij} + \delta_{ji} \leq 1 & \forall\, 1 \leq i,j \leq N, i \neq j & (7)\\
p_i + u_i = c_i & \forall\, 1 \leq i \leq N & (8)\\
a_i \leq u_i \leq (T - p_i) & u_i \in R^+, \forall\, 1 \leq i \leq N & (9)\\
0 \leq v_i \leq (S - s_i) & v_i \in R^+, \forall\, 1 \leq i \leq N & (10)\\
\sigma_{ij} \in \{0,1\}, \delta_{ij} \in \{0,1\} & \forall\, 1 \leq i,j \leq N, i \neq j & (11)
\end{cases}$$

where:

S - pontoon length
T - length of the planning horizon
N - total number of arriving yachts N=10
p_i - working time i , $1 \leq i \leq N$
s_i - the width of the craft i , $1 \leq i \leq N$
a_i - arrival time i , $1 \leq i \leq N$

and the variables :

w_i - coefficient of importance i , $1 \leq i \leq N$
u_i - time of berthing i , $1 \leq i \leq N$
v_i - initial position at the quay i , $1 \leq i \leq N$
c_i - time of departure of the craft i , $1 \leq i \leq N$

$$\sigma_{ij} = \begin{cases} 1 \text{ if ship i is completely to the left of ship } j \text{ in the space-time diagram} \\ 0 \text{ otherwise} \end{cases}$$

$$\delta_{ij} = \begin{cases} 1 \text{ if ship } i \text{ } is \text{ completely below ship } j \text{ in the space-time diagram} \\ 0 \text{ otherwise} \end{cases}$$

Given that :

- The total time available is 15 days, i.e. 360 hours (T=360)
- Berths are continuous along a 30 m long quay (S=30)
- All vessels dock directly at the quay to be connected to the utilities.
- The importance depends on the width of the craft:
  $w_i = 1$ if $s_i < 5$ m , and $w_i = 2$ if $s_i \geq 5$ m (for these vessels mooring assistance is required)
- As u_i - being the arrival time, we can consider that $u_i < a_i$, which means that the docking time is not equal to the arrival time.

The algorithm will generate the service plan for ships in a way that minimises the total time that ships will spend in port.

But the time in port has two components: the waiting time at the berth and the service time, which in the case of these ships is the time the ship intends to spend in port (it is not variable and is communicated at the voyage planning stage).

For the case study presented and the values described in Table 4.4, the model will be updated as follows :

- Due to the fact that the Constanta - Tomis marina has a limited berthing basin, which is often crowded with traffic, the arrival time becomes equal to the berthing time, which means that $u_i = a_i$, for $i = 1...10$
- The time of the mooring service is announced by the sailing vessel, and $c_i$is equal to the length of stay.
- The unknowns are the moments $a_i = u_i$

The objective function becomes :

$$F = \sum_{i=1}^{N} w_i * (c_i - a_i) \qquad (12)$$

and the restrictions turn into:

$$a_j - a_i - p_i - (\sigma_{ij} - 1) * 360 \geq 0 \qquad \forall\, 1 \leq i,j \leq N, i \neq j \qquad (13)$$

$$v_j - v_i - s_i - (\sigma_{ij} - 1) * 30 \geq 0 \qquad \forall\, 1 \leq i,j \leq 10, i \neq j \qquad (14)$$

$$p_i + a_i = c_i \qquad \forall\, 1 \leq i \leq 10 \qquad (15)$$

$$a_i = u_i \leq (360 - p_i) \qquad u_i \in R^+, \forall\, 1 \leq i \leq 10 \qquad (16)$$

$$0 \leq v_i \leq (30 - s_i) \qquad v_i \in R^+, \forall\, 1 \leq i \leq 10 \qquad (17)$$

$$\sigma_{ij} \in \{0,1\}, \quad \delta_{ij} \in \{0,1\} \qquad \forall\, 1 \leq i,j \leq 10\,, i \neq j \qquad (18)$$

In summary, the constraint system of the linear programming program generated by the case study consists of:

- A_{10}^2 type inequalities (4.32), total 45;

- A_{10}^{2} type inequalities (4.33), total 45;
- Inequalities of type (4.34), (4.35) and (4.36), total 30.

Thus, the constraint matrix A has 120 rows corresponding to the constraints and 10 columns generated by the variables $u_i = a_i$. The solution found using the MATLAB progrm, linprog instruction has been listed in column (3) of Table 11.For the second step, the data in Table 11 are used.

Table 11. The measures involved in the problem

Yacht	Width $(s)_i$	Docking time $(at)_i$ hours	Service time $(p)_i$		Departure time $(c)_i$	Importance w_i
			hours	days	hours	
1	4	6	144	6	150	1
2	4,3	8	168	7	176	1
3	3,4	9	72	3	81	1
4	5	10	216	9	226	2
5	4,5	90	96	4	186	1
6	5,5	200	72	3	272	2
7	4	224	96	4	320	1
8	3,5	172	72	3	244	1
9	4,2	180	24	1	204	1
10	3,4	240	48	2	288	1

The following must be taken into account when calculating s_i and placing the craft:

- The initial distance between the quay and the first craft is 2m, which means that $v_1 = 2$.
- The distance between two boats must be 1.5 m to allow room for manoeuvring and also to mount the protective balloons.

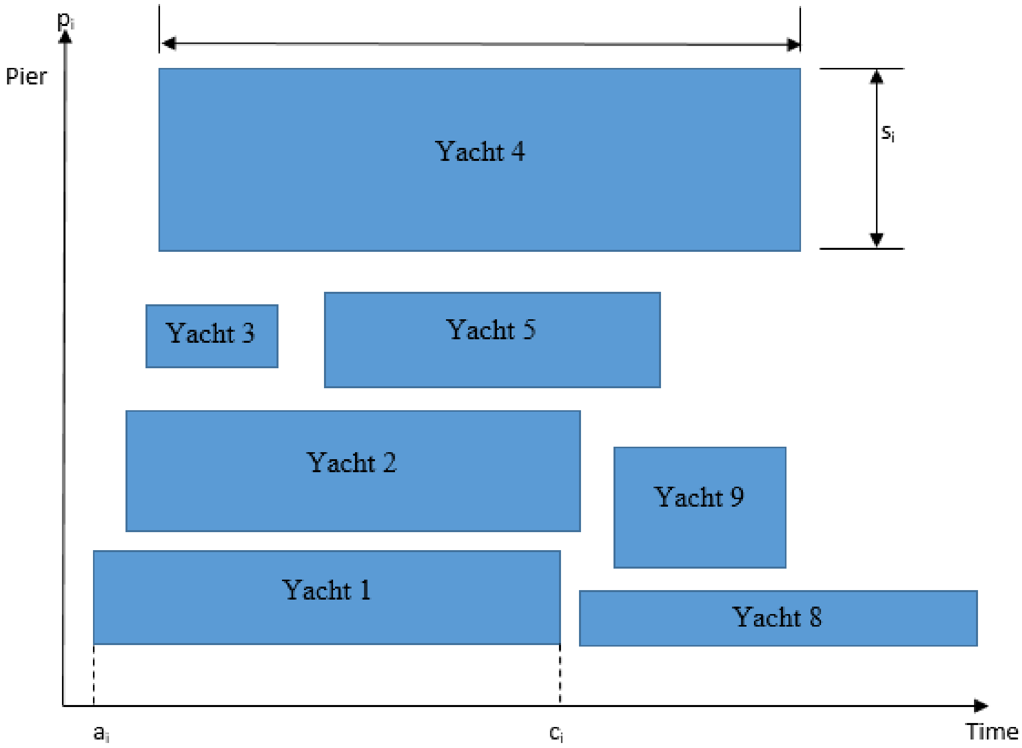
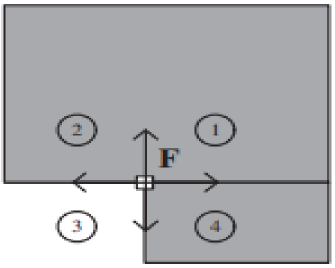


Figure 10. Space-time diagram for continuous allocation (Source:Author)

Craft A6, A7 and A10 could not be placed. To identify possible locations for these, both the importance of the remaining vessels and the ABCD rectangle defined in the space-time diagram are used.
Nodes E, F, G, H, I, J, K, L, B, C define the empty space (V) in which vessels 6 and 7, 10 could be positioned.

The vectors associated to the nodes according to Lee, (2010), are constructed by assigning to each node the vectors from $RxRxRxR$ that describe the state of the four quadrants that a Cartesian landmark originating in the node would form.



If the quadrant is occupied it is assigned a value of 0 because it does not provide space that could be occupied or it crosses the domain boundary and the unoccupied facility could not be used without violating the restrictions of the problem and 1 if it is unoccupied.
The result is E: (1, 1,1, 0) ; F: (1, 0, 1, 1) ; G: (0, 0, 0, 1) ; H: (0, 1, 1, 1) ; I: (1, 1, 0, 1,) ; J: (1, 0, 0, 0) ; K: (1,1, 0,1) ;L: (1, 0, 0, 0).
Five classes of vectors are formed, depending on the sum of the components, (e.g. class C1 contains only vectors J and L).

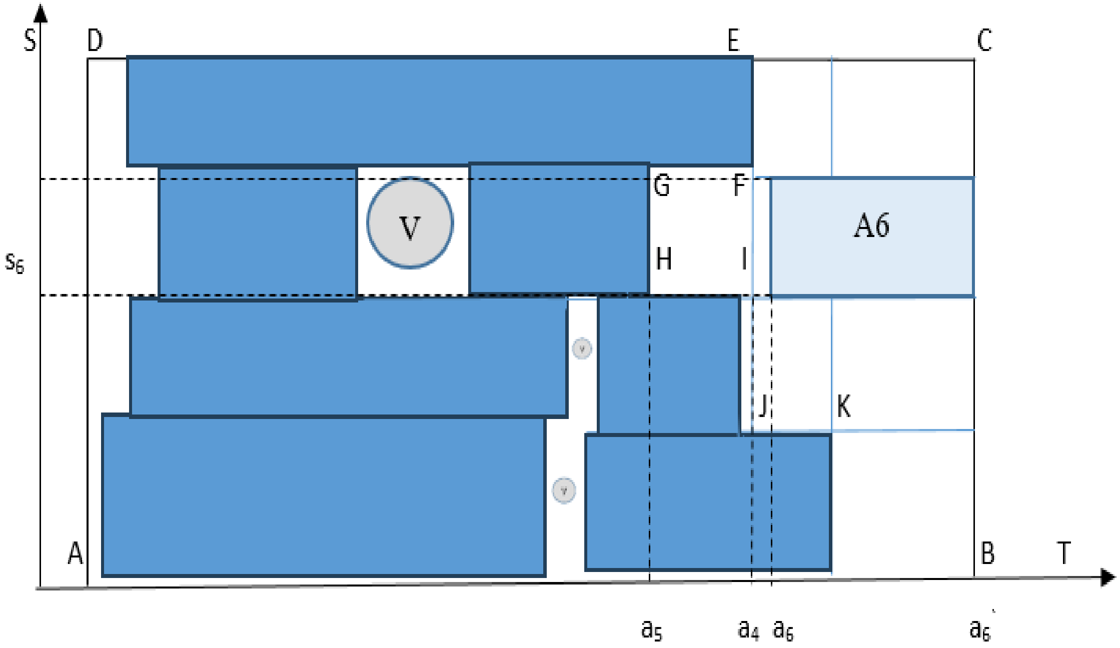


Figure 11. Position of A6 (Source: Author)

For craft A6, the mooring at the berth will be as shown in Figure 11 :

- beam s_6 = 5,5 m
- the segment a_6 - a_6 ` is equal to the time spent in port which is 72h starting from a_6 (determined by IJ) so = 204h

The final layout is as shown in Figure 12 and the BLKJIHGFEC search domain accepts all craft at the times indicated by the algorithm run in Step 1.

This method allows the planning of arrivals at a marina directly, without waiting, and being done in advance it also allows the vessels to rotate to their intended ports with minimum waiting times.

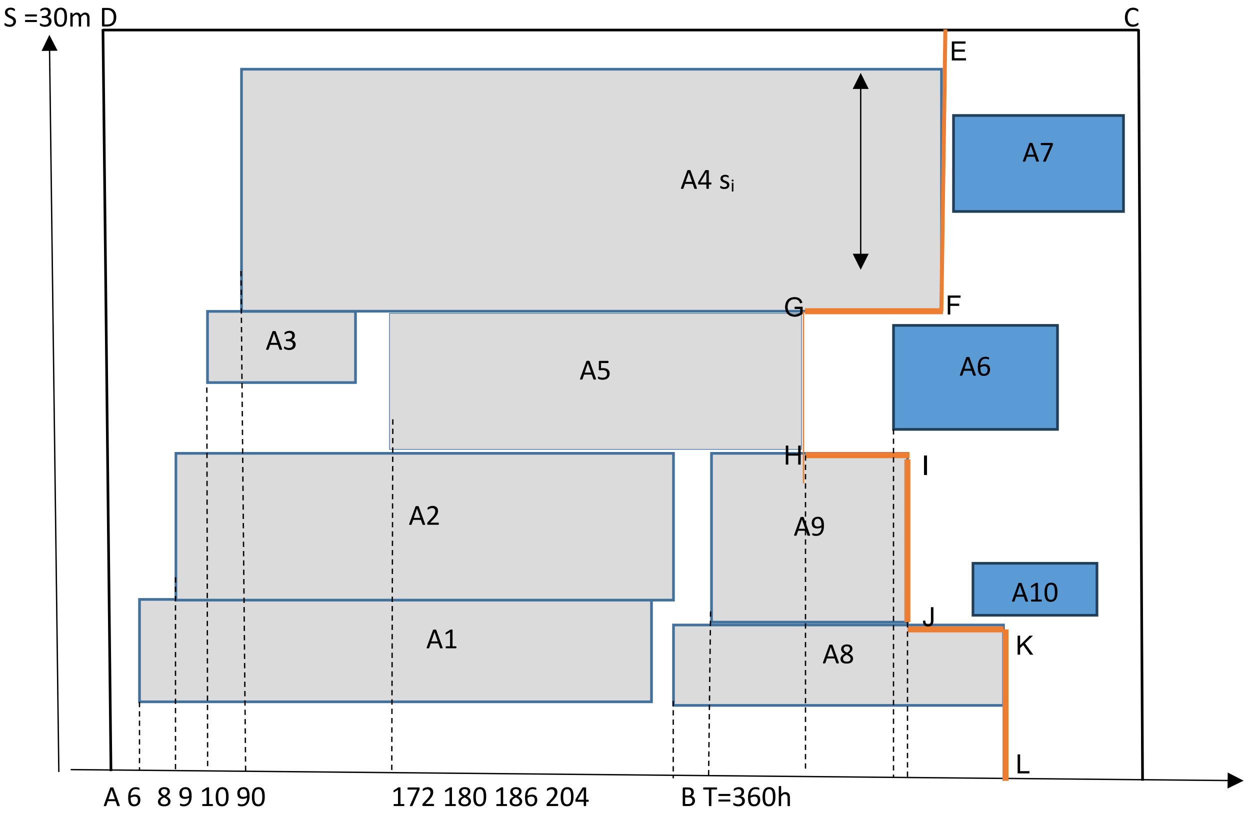


Figure 12. Final layout

The usefulness of applying the modified algorithm results from:

1. Waiting creates a burden on the vessels with resources that would be consumed during their time, as not being connected to the utilities offered by the port, consumption would be made from supplies
2. Prolonged idling generates additional pollution that would affect the air quality of the communities where the marinas are located.

4.2 Vessel speed optimization using the backtracking algorithm, application

For maritime transport, optimising fuel consumption remains a primary concern, especially for comercial and even offshore vessels.

Given the current market landscape, there is an ageing fleet including for multi-purpose offshore vessels, such as even tugs, which can be used in different roles, including to provide platform support. While studies are focusing on the development of new advanced propulsion systems and technologies, such as hybrid electric propulsion, it is important to understand the continued relevance and potential benefits of optimising the operational process of older vessels.

The case study presents and details a backtracking algorithm adapted for optimizing the fuel consumption of a tug operating as a platform support/power supply vessel (MPSV). The main objective is to discern the optimal speed that would result in minimum fuel consumption while respecting operational constraints.

Backtracking is an algorithm for systematically searching all possible combinations in a solution space. A partial solution is defined by a combination of variables satisfying a set of constraints. The algorithm progressively expands a partial solution to a complete solution in which all variables are assigned. All intermediate combinations are tested to complete the problem constraints and the optimal allocation. Whenever the test fails, the algorithm reverts to the most recent feasible partial solution. The algorithm terminates when all variables are successfully allocated.

Methodology:

A Platform Supply Vessel (PSV) is used to transport goods and personnel from a port facility to various offshore structures such as drilling rigs or production platforms. Typically, the voyage is considered a closed loop and provides a circular transport with multiple stops. The voyage involves different speeds ranging from full speed to zero in certain situations where platforms require waiting times.

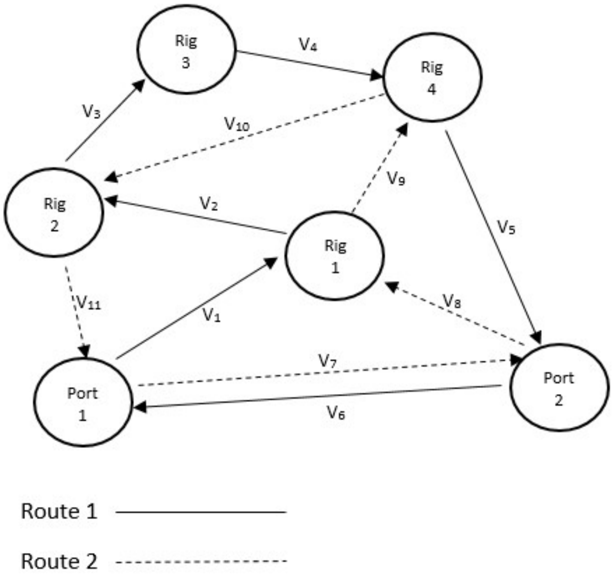


Figure 13. Potential vessel routes and speed options. (Source: Author)

Each leg of the journey can be divided into smaller legs, depending on the speed restrictions in the navigation area.
Mathematical model:

The objective of the problem is to minimise total fuel consumption:

$$m_f = \sum_{i=0}^{n-1} m_{f\,(s_i, s_{i+1})} \tag{19}$$

where,
m_f - is the total mass of fuel used
s_i - travel segment
t_i - departure time

The mass of fuel burned m_f of each route segment is evaluated by numerically integrating the fuel mass flow versus time as shown in equation :

$$m_{f s_i}^{s_{i+1}} = \int_{ti}^{tj} m_f(t)dt \tag{20}$$

If N is the total number of segments making up the trip, then the total mass M is equal to:

$$M = \sum_{i=1}^{N} m_f s_i{}^{s_{i+1}} \tag{21}$$

where the ship is assumed to travel from the point x_i at the time t_i to the point x_{i+1} at the time t_{i+1} and the total consumption of the voyage M will be the sum of the fuel masses for each segment.

In this study, optimising fuel consumption is considered as an objective function. The fuel consumption of a ship can be calculated by multiplying the fuel flow by the time in which the fuel is consumed.

$$FC = F \cdot t \tag{22}$$

where,
FC = fuel consumption [kg]
F = mass flow rate [kg/h]
T = time [h]

A time constraint is added, as the duration of the journey must not exceed $\bar{T}$.

$$\sum_{i=1}^{N} t_i(v_i, \Delta v_i) \leq \bar{T} \tag{23}$$

The resultant hydro-aerodynamic forces act on a ship moving at a constant speed, V. The ship's drag is the projection of the resultant of the hydro-aerodynamic forces acting on the ship in the direction of the speed of travel (Obreja et al.,2003). The calculation of the ship's loss of speed in different weather conditions (wind and sea) is based on the Kwon method, which can be used for its simplicity and due to the specificity of a supply ship in coastal voyages (Kwon,2008).

$$\frac{\Delta V}{V_1} 100\% = C_\beta C_U C_{form} \tag{24}$$

$$\Delta V = V_1 - V_2 \tag{25}$$

$$V_1 = F_n \sqrt{L_{pp} g} \tag{26}$$

where:

Fn = Froude number (dimensionless number used in fluid dynamics to compare flow inertia with an external field)

ΔV= loss of ship speed [m/s],

V_1 = speed of vessel in calm water [m/s],

V_2 = speed of the vessel in selected weather conditions [m/s],

C_β = the velocity direction reduction coefficient, which depends on the direction of the weather and the Beaufort number BN,

C_U = the speed reduction coefficient, which depends on the ship's block coefficient CB, the loading conditions and the Froude number Fn,

C_{form} = hull form factor, which depends on the type of ship, Beaufort number BN and ship displacement D (t),

BN - Beaufort number (dimensionless)

The calculation of the coefficients is described in the following tables:

Table 12. Weathering coefficient C_β

Address	**Angle β**	**Reduction coefficient C_β**
From Proof	**0 - 30^0**	$C_\beta = 1$
Travers test	**30^0 - 60^0**	$C_\beta = \frac{1.7 - 0.03((BN-4)^2)}{2}$
Travers pupa	**60^0 - 150^0**	$C_\beta = \frac{0.9 - 0.06((BN-6)^2)}{2}$
From the stern	**150^0 - 180^0**	$C_\beta = \frac{0.4 - 0.03((BN-8)^2)}{2}$

Table 13. Speed loss coefficient C_U

Block coefficient C_B	Loading	Speed reduction C_U
0.55	Normal	$1.7 - 1.4F_n - 7.4(F_n)^2$
0.60	Normal	$2.2 - 2.5F_n - 9.7(F_n)^2$
0.65	Normal	$2.6 - 3.7F_n - 11.6(F_n)^2$
0.70	Normal	$3.1 - 5.3F_n - 12.4(F_n)^2$
0.75	Maximum or normal	$2.4 - 10.6F_n - 9.5(F_n)^2$
0.80	Maximum or normal	$2.6 - 13.1F_n - 15.1(F_n)^2$
0.85	Maximum or normal	$3.1 - 18.7F_n - 28.0(F_n)^2$
0.75	Ballast	$2.6 - 12.5F_n - 13.5(F_n)^2$
0.80	Ballast	$3.0 - 16.3F_n - 21.6(F_n)^2$
0.85	Ballast	$3.4 - 20.9F_n - 31.8(F_n)^2$

Table 14. Coefficient C $_{\text{form}}$

Vessel type and cargo	Coefficient C_{form}
All vessels (except container ships) fully loaded	$0.5BN + \frac{BN^{6.5}}{2.7\Delta^{2/3}}$
All vessels (except container ships) in ballast	$0.7BN + \frac{BN^{6.5}}{2.7\Delta^{2/3}}$
Containers under normal loading conditions	$0.5BN + \frac{BN^{6.5}}{22\Delta^{2/3}}$

Depending on the scale of the BN, speed and navigation conditions along the route vary for each segment of the journey.

Numerical application:

To illustrate the optimization of ship speed using the inverse tracking algorithm, we use a ship voyage as in Figure 14.

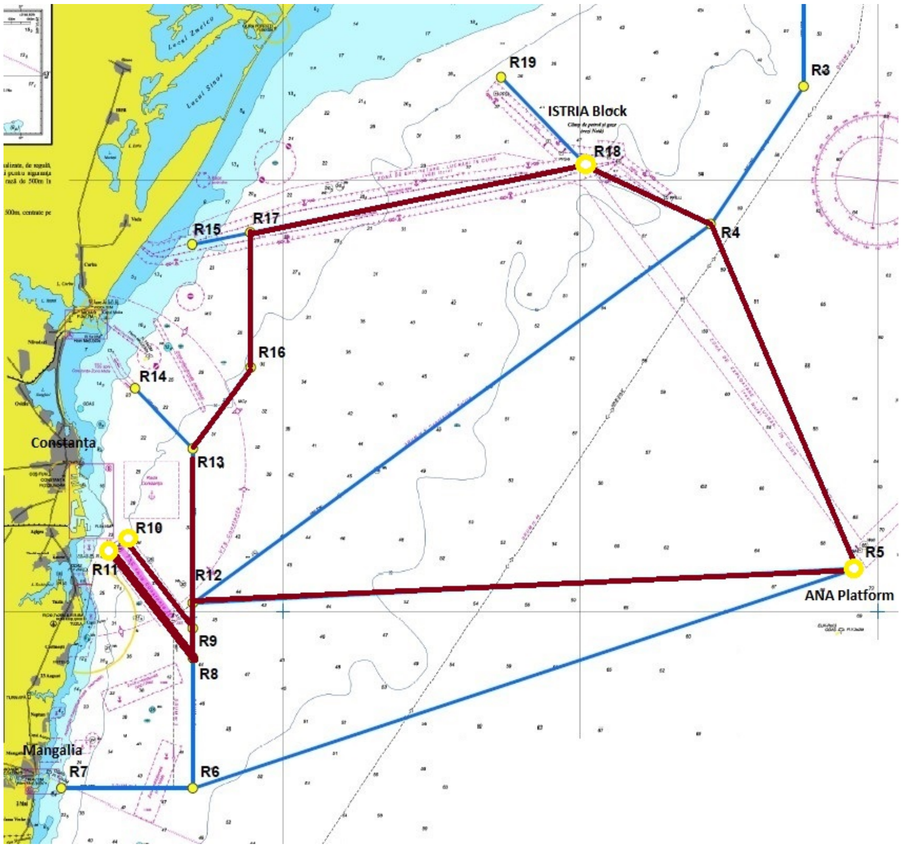


Figure 14. Recommended routes and landmarks (Source: Author)

Individual segments have the following properties:

Segment	Distance (Nm)
R11 - R8	13.17
R8 - R9	2.9
R9 - R12	2.47
R12 - R13	14.96
R13 - R16	9.83
R16 - R17	13.06
R17 - R18	34.59
R18 - R4	13.86
R4 - R5	36.5
R5 - R12	67.35
R12 - R9	2.47
R9 - R10	10.93

The vessel's speed/fuel characteristics are listed in Table 15, with the lever position representing the speed selection.

Table 15. Speed/fuel characteristics (Source: Author)

Leverage position (%)	Speed (kts))	Consumption (l/h)	Consumption (l/Nm)
5	3.2	48.64	15.2
15	5.1	94.86	18.6
25	6.5	131.95	20.3
35	7.9	194.34	24.6
45	9	241.2	26.8
55	9.9	289.47	29.24
65	10.8	347.22	32.15
75	11.4	411.08	36.06
80	11.9	495.03	41.59
85	12.3	544.64	44.28
90	12.6	582.49	46.23
95	12.8	628.73	49.12
100	13.0	688.87	52.99

Ten different scenarios were chosen for algorithm verification.The differences are in weather condition and displacement :

Script	Travel time [h]	Weather conditions	Displacement (tonnes)
Scenario 1	18	Fully fuelled ship, weather scale BN =1	700.46
Scenario 2	18	Fully fuelled ship, weather scale BN =2	700.46
Scenario 3	20	Fully fuelled ship, weather scale BN =3	700.46
Scenario 4	24	Ship fully loaded with fuel, oil, provisions and 50t of cargo on board, weather scale BN =1	811.91
Scenario 5	24	Ship fully loaded with fuel, oil, provisions and 50t of cargo on board, weather scale BN =2	811.91
Scenario 6	24	Ship fully loaded with fuel, oil, provisions and 50t of cargo on board, weather scale BN =3	811.91
Scenario 7	22	Vessel loaded to maximum allowable draught, weather scale BN =2	839.19
Scenario 8	22	Vessel loaded to maximum allowable draught, weather scale BN =3	839.19
Scenario 9	19	Ship loaded with 50% fuel, weather scale BN =2	743.42
Scenario 10	19	Ship loaded with 50% fuel, BN =3	743.42

Voyage Condition	Engine speed [kts]					
	R11-R8	R8-R17	R17-R18	R18-R5	R5-R12	R12-R10
1	9.90	10.80	9.90	9.90	9.90	9.90
2	10.80	11.40	11.40	11.40	10.80	11.40
3	12.80	12.60	12.80	12.60	12.60	12.60
4	9.90	10.80	9.90	9.90	9.90	9.90
5	10.80	11.40	11.40	11.40	10.80	11.40
6	12.60	12.60	12.80	12.60	12.60	12.60
7	10.80	11.40	11.40	11.40	10.80	11.40
8	12.60	12.60	12.80	12.60	12.60	12.60
9	10.80	11.40	11.40	11.40	10.80	11.40
10	12.80	12.80	12.60	12.60	12.60	12.60

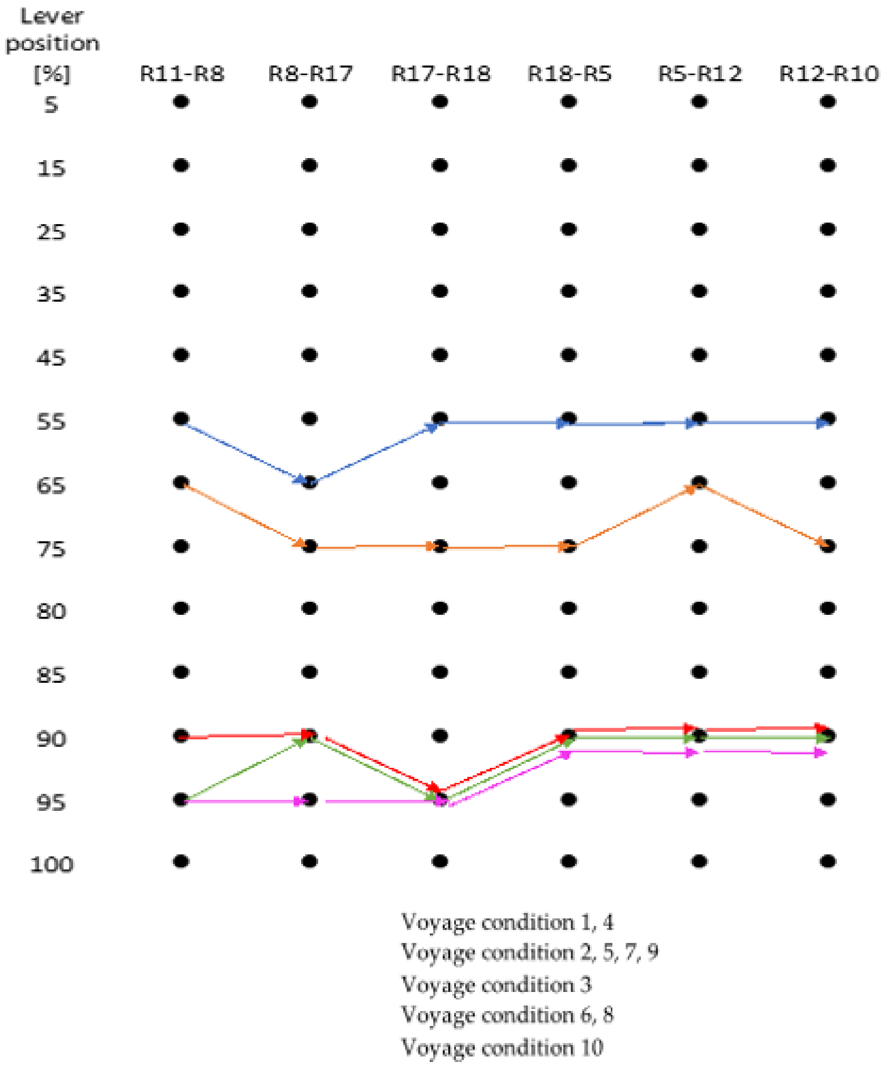
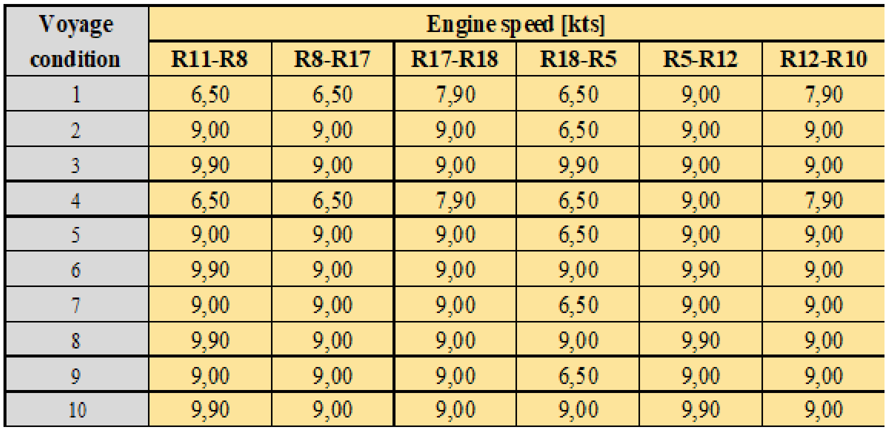


Figure 15. Optimised choice of speed/lift for travel time T = 24 h (Source: Author)



Voyage condition	Engine speed [kts]					
	R11-R8	R8-R17	R17-R18	R18-R5	R5-R12	R12-R10
1	6,50	6,50	7,90	6,50	9,00	7,90
2	9,00	9,00	9,00	6,50	9,00	9,00
3	9,90	9,00	9,00	9,90	9,00	9,00
4	6,50	6,50	7,90	6,50	9,00	7,90
5	9,00	9,00	9,00	6,50	9,00	9,00
6	9,90	9,00	9,00	9,00	9,90	9,00
7	9,00	9,00	9,00	6,50	9,00	9,00
8	9,90	9,00	9,00	9,00	9,90	9,00
9	9,00	9,00	9,00	6,50	9,00	9,00
10	9,90	9,00	9,00	9,00	9,90	9,00

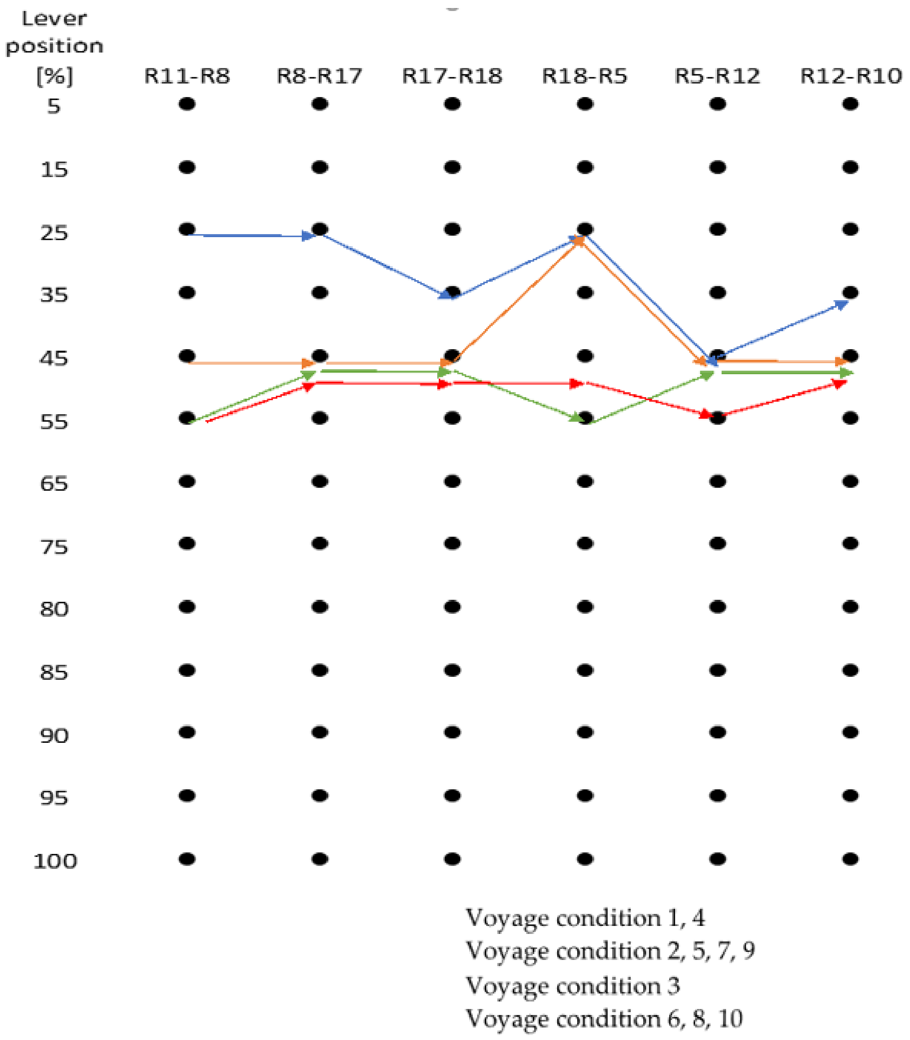


Figure 16. Optimised choice of speed/lift for travel time T = 32 h (Source: Author)

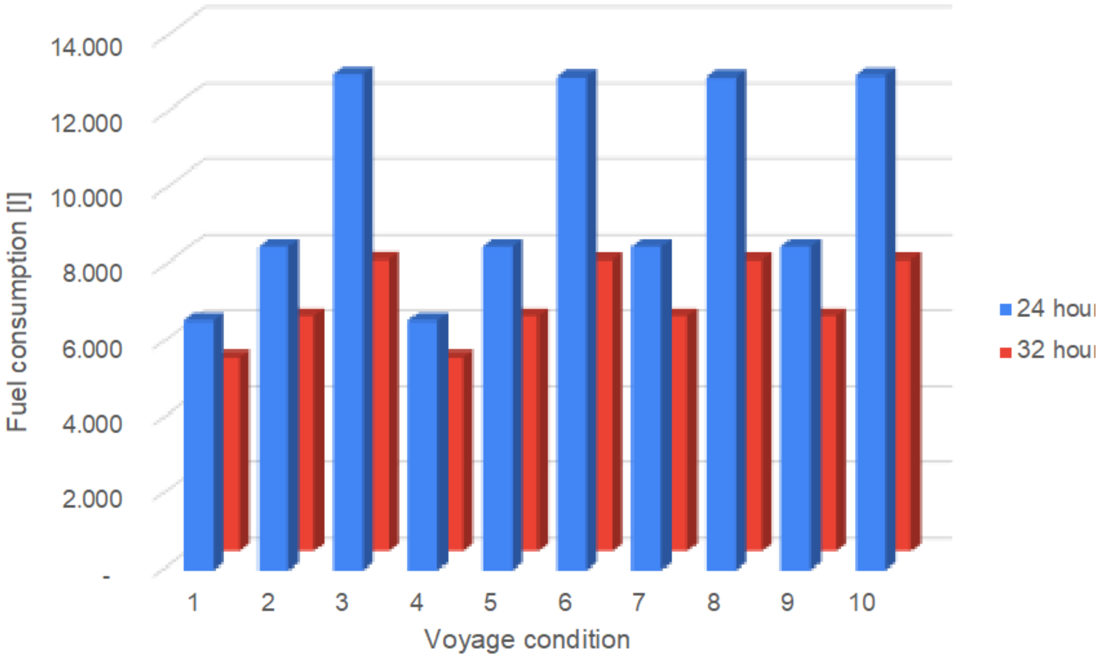


Figure 17. Fuel consumption for different travel conditions and travel time limits (Source: Author)

The results(figure 17) highlight the trade-offs between speed and fuel consumption for two travel time limits: 24 hours (figure 15) and 32 hours (figure 16).

While higher speeds allow faster transit, they come at the cost of higher fuel consumption. Lever position directly influences engine speed. Higher lever positions lead to higher engine speeds. For example, in condition 1, a lever position of 55% corresponds to an engine speed of 9.90 knots, while in condition 3, a lever position of 95% corresponds to an engine speed of 12.80 knots.

5. ENERGY EFFICIENCY IN SHIPPING OPERATIONS

The International Maritime Organisation (IMO) has implemented several measures to reduce greenhouse gas (GHG) emissions from shipping, recognising the sector's significant contribution to global emissions.

Main measures include the use of :

- Energy Efficiency Design Index (EEDI)
- Energy Efficiency Operational Indicator (EEOI)
- Ship Energy Efficiency Management Plan (SEEMP)
- Energy Efficiency Index of Existing Ships (EEXI)
- Carbon Intensity Indicator (CIA)
- Mandatory fuel consumption data collection system

These measures are part of the "Initial IMO GHG Strategy" adopted in 2018, which aims to reduce the carbon intensity of international shipping by at least 40% by 2030 and to reduce total annual GHG emissions from international shipping by at least 50% by 2050 compared to 2008, while continuing to work towards their total elimination.

Table 16. Possible technological optimisations (Source: Author)

Technology	Description	Benefits	Disadvantages
Speed reduction	Operating vessels at low speeds	Reduces fuel consumption	Increased travel time
Air lubrication systems	Pumping air under the hull	Reduces friction between hull and water	Special installation, costs
Waste heat recovery	Capture and reuse of heat generated by ship engines.	Turns wasted energy into electricity	Complexity in implementation, installation costs
Rotor blades	Large cylindrical blades that rotate vertically using the Magnus effect.	Provides additional propulsion	Requires space, installation and maintenance costs
Integration of solar and wind energy	Incorporating solar panels and wind turbines.	Top up your energy needs	Variability of energy source, installation costs, space requirements
Alternative fuels	Using cleaner alternatives to traditional marine fuels.	Cleaner burning, significantly reducing carbon and sulphur emissions.	Accessibility, cost, need for supply infrastructure
Electric and hybrid propulsion	Ships with electric motors, either fully electric or hybrid.	Reduces or eliminates emissions depending on propulsion type.	High initial costs, limitations in autonomy
Energy management systems	Systems that monitor and optimise the ship's energy consumption.	Ensures maximum efficiency of production and consumption	Complexity, implementation and maintenance costs

		systems	
Improved Antifouling Coatings	Coatings that prevent the growth of organisms on the hulls of ships.	Reduces resistance to forward movement caused by the growth of organisms	Application costs, possible need for periodic renewal
Hull design	Optimising hull shape for minimum water resistance.	Improved fuel efficiency, lower emissions	Design and implementation costs, potential trade-offs in other areas
Propeller design	Advanced designs such as counter-rotating propellers and propeller head cover fins.	Increased propulsion efficiency, reduced fuel consumption	Design and manufacturing costs, potential performance trade-offs

Considering the components of sustainability defined in chapter three and the potential technological solutions, we carried out a case study on a passenger ship, where by replacing the lighting control systems we sought to reduce the energy consumption of the ship. Depending on the working regime of the ship we achieved significant savings ranging from 3.64% to 11.57%.

5.1 Energy optimization for a passenger vessel, case study

Lighting is an important source of electricity consumption on passenger ships, with a high potential for savings.

Replacing old lamps, ballasts and luminaires is the most common lighting retrofit strategy, with great savings potential. By switching to more energy efficient lighting technologies, a considerable amount of energy can be saved (Mahlia,2005). The study by (Trifunovic et al.,2009) showed an energy saving potential of up to 27% in the residential sector and 30% in the commercial sector.

The research method used in this analysis is a combination of a case study and a comparative analysis (Figure 18). The case study was carried out on a cruise ship built in 1997, examining its current lighting system and the potential for improving energy efficiency. The study is grounded in the context of rising fuel prices and the challenges they present to cruise ship operators in the paradigm of shipping sustainability.

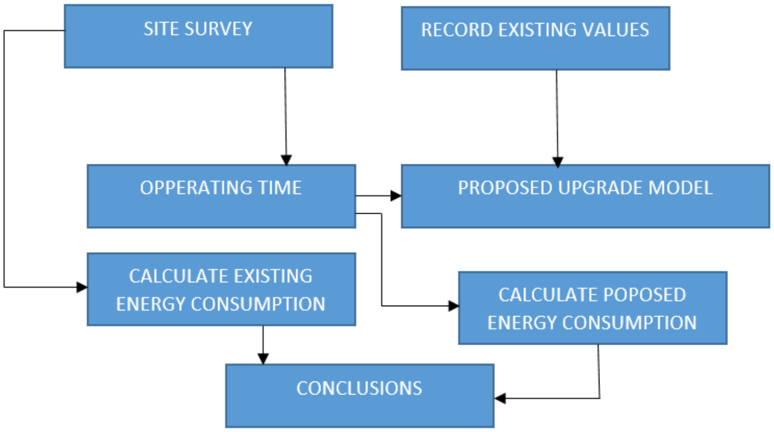


Figure 18. Research framework (Source: Author)

Vessel parameters :

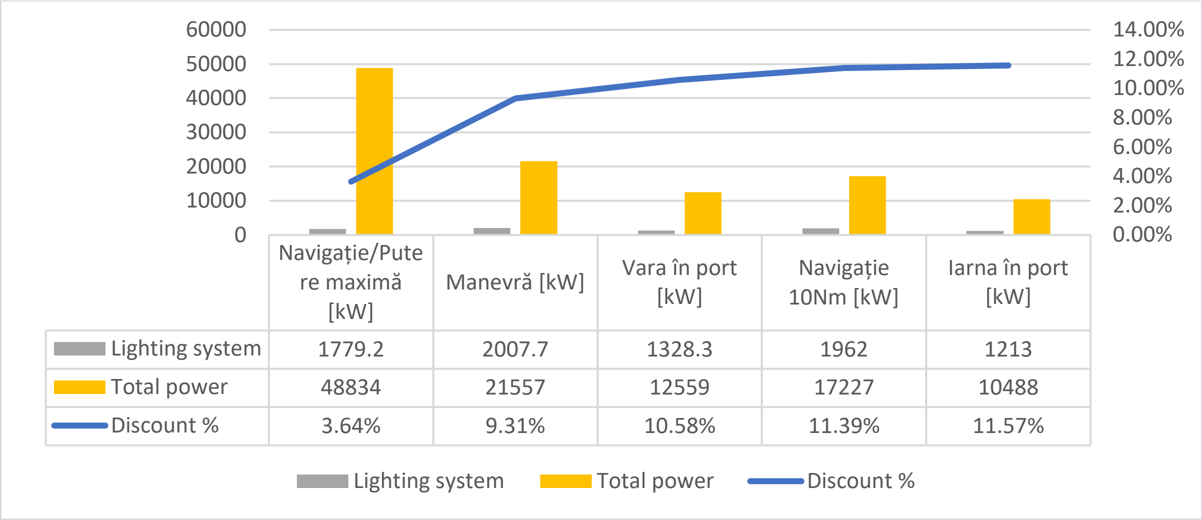
Propulsion	HV Diesel Electric
Gross Net (International)	83,338 t
Net (International)	59,472 t
Total power	57,600 kW
Cruising speed	22 knots
Rated voltage	6.600 V
Frequency/pf	60Hz/0.8
Total number of lamps	9669
Lighting power - watts	261971

The methodology is highly practical and applied, focusing on real-world challenges and potential solutions in the context of a specific case. It combines elements of benchmarking, energy efficiency analysis, calculation of CO_2 emissions and builds on case study research to provide a comprehensive understanding of the potential for improving energy efficiency in cruise ship lighting systems.

Lighting control systems are replaced by ECG (electronic) models instead of CCG (conventional) ones.

Table 17. Differences between ECG and CCG (Source: Author)

Parameter	ECG (electronic ballast)	GCC (electromagnetic ballast)
Energy efficiency	Large (up to 30% more efficient than magnetic ballasts)	Low
Costs	Higher initial costs but lower operational costs due to energy efficiency	Lower initial costs but higher operational costs due to lower energy efficiency
Working principle	Operates at high frequencies (20,000 - 60,000 Hz), eliminating flicker and hum	Operates at a low frequency (60 Hz), which can cause visible flickering and buzzing
Working life	Longer lifetime due to lower heat generation and advanced technology	Shorter lifetime due to higher heat generation and older technology
Technology	Advanced, uses electronic components	Older, uses magnetic core and coil transformer technology
Total harmonic distortion (THD)	Lower THD (<10%), leading to fewer power quality problems	Higher THD (20% - 50%) can lead to power quality problems
Power factor	High (close to 1), indicating efficient use of electricity	Lower (less than 1), indicating less efficient use of electricity
Heat generation	Lower heat generation due to high energy efficiency	Higher heat production due to low energy efficiency
Noise level	Quieter operation due to high frequency operation	Noisier operation due to low frequency operation
Compatibility with dimming systems	It is generally more compatible with dimming systems, but it depends on a particular model.	Generally less compatible with dimming systems, but depends on a particular model.



	Navigație/Putere maximă [kW]	Manevră [kW]	Vara în port [kW]	Navigație 10Nm [kW]	Iarna în port [kW]
▬ Lighting system	1779.2	2007.7	1328.3	1962	1213
▬ Total power	48834	21557	12559	17227	10488
━ Discount %	3.64%	9.31%	10.58%	11.39%	11.57%

Figure 19. Lighting energy consumption balance (Source: Author)

The lighting system's power consumption ranges from 3.64% to 11.57% of the total power under different conditions. While this is a relatively small percentage, given the large amount of power ships require, even small improvements in lighting efficiency could result in significant energy savings. Keeping in mind that the vessel is a passenger cruiser which spends a lot of time in port or at cruising speeds, the improving of the lighting system efficiency is recommended.

5.2 Results

Replacing outdated control equipment with contemporary ECGs in the engine room and crew areas resulted in a significant energy saving of 31.2%. This saving was boosted to 49.69% by a complete upgrade of the lighting system in other public areas. Such energy savings translate directly into reduced fuel consumption, assuming that the ship's energy source comes mainly from fuel. Reduced fuel consumption means reduced CO_2 emissions, which would lower the denominator in the EEDI formula.The findings are consistent with current research, which has found that a reduction in energy consumption of between 17 and 40% can be achieved by retrofitting with ECG.

Percentage of energy consumed from lighting: The ship's lighting system accounts for about 11% of the ship's total energy consumption, both in port and at cruising speeds. Therefore, if lighting system energy consumption can be reduced by approximately 49.69%, this translates to:

$$Total\ Energy\ savings = 0.4969 \cdot 0.11 = 0.054659\ or 5.4659\%$$

A 5% reduction in energy consumption as a result of the lighting retrofit means a similar 5% reduction in emissions, as the ship's emissions are directly proportional to energy consumption (assuming constant fuel properties), which would reduce the denominator in the EEDI formula, resulting in a more favourable (lower) EEDI value.

This demonstrates the potential benefits of upgrading and modernising systems on ships to achieve greater energy efficiency and align with EEDI targets.

In conclusion, upgrading the lighting system and replacing old control equipment with ECGs can play a significant role in improving a ship's energy efficiency, making it more compliant with EEDI standards.

CONCLUSIONS AND CONTRIBUTIONS

Shipping is cost-effective and efficient but presents notable sustainability challenges.Current research and the state of the industry show that the world fleet is ageing. Although the IMO consistently regulates the industry and is focused on sustainable development, measures are poorly implemented and companies are reluctant to invest. The reasons are geopolitical instability, armed conflict, post-pandemic economic impact, technological barriers or lack of funding.

Through a holistic approach the sustainability issue can be managed by optimising the constituent factors taking into account causal relationships. The paper shows that the maritime industry is actively engaged in improving sustainable practices and understands the need to reduce environmental impacts and pollution.

The case studies, the applications carried out and presented in the paper, can contribute to the sustainable development of shipping. Thus:

- The local survey of Romanian marinas showed a growing interest in this type of recreational water transport, with the number of boats and visits on a positive trend. The study fills a gap in the literature compared to the situation in neighbouring countries. For a sustainable development, the analysis of selected indicators highlighted shortcomings that need to be addressed.

- Exploring optimization methods based on mathematical models in the field of operations research by implementing an optimization model in marinas can streamline the scheduling and allocation of vessels at the quay. The method can reduce waiting times, limit the risk of harbour congestion, avoid accidents or environmental pollution through spills of pollutants due to limited storage capacity. This type of algorithm can also be solved by genetic algorithms and can be implemented in a mobile application that will contribute to the digitisation of nautical transport.

- For energy inefficient ships in operation, where technological improvement is difficult to achieve, we proposed a method to optimize the ship's path by backtracking algorithm. This algorithm allows the choice of an optimal speed configuration given constraints imposed by the weather and the time window. This achieves reductions in fuel consumption and greenhouse gas emissions, increasing operational efficiency and minimising environmental impact.

- Energy efficiency is one of the factors that can lead to drastic reductions in atmospheric emissions from ships. One method that can be adapted to less efficient passenger ships is to replace lighting control systems. In the case study we showed that under certain ship operating conditions, the energy consumed can reach up to almost 12% of the total power produced on board. The energy balance calculation showed that a replacement with electronic control systems can bring reductions of 5.5% of the total energy produced by the ship, which is significant.

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