IOSUD –„DUNĂREA DE JOS” UNIVERSITY OF GALAȚI
Doctoral School for Mechanical and Industrial Engineering

PhD THESIS SUMMARY

STUDIES RELATED TO THE SHIP BEHAVIOUR IN THE EUROPEAN SEAS

PhD Student,
Eng. Ana-Maria CHIROŞCĂ

PhD Supervisor,
Prof. eng. Liliana-Celia RUSU, PhD Habil.

The PhD thesis was carried out with the financial support of the project

"Academic excellence and entrepreneurial values - scholarship system to ensure opportunities for training and development of entrepreneurial skills of doctoral and postdoctoral students - ANTREPRENORDOC"

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Series: I6: Mechanical Engineering No. 68

GALAŢI

2023

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Seria: I6: Inginerie Mecanică Nr. 68

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Galați April 2023

Contents

Introduction

Motivation and objectives

The majority of Europe's borders are marine. The Atlantic Ocean, Artic Ocean, Black Sea, and Mediterranean Sea, all encircle the continent. Each of these is separated into seas, straits, and canals that connect interior river navigation and maritime navigation with the other continents.

During both upswings and downturns in the economy, such as the COVID-19 epidemic, the 2008 global economic crisis, or the current situation with the conflict between Russia and Ukraine, the need for freight and passenger transportation continues to grow. Nowadays, maritime transport is the main mode of transport for both exports and imports because of the speed at which ships can sail today, the costs of such transport, the capacity to move vast amounts of cargo, the congestion of other types of transport and, most importantly, the need to reduce pollution.

For Europe's economy, ports are crucial. They serve as the primary nodes of the global trade network, and many of the most significant cargo ports are in Europe. Climate change has made shipping in the European basin difficult in recent years, therefore transport ships must be connected to the potential effects that might have on their operability. The size of several ship types has consistently increased over the past decade, particularly oil tankers, port-containers, and RO-RO ships. Furthermore, the ports that these kinds of ships frequently use, and the size of the waterways present restricted transport circumstances. To provide the most up-to-date picture of the maritime traffic situation in the European sea basins and trends in maritime transport, one of the objectives was to carry out an analysis highlighting these issues.

Climate has a direct impact on shipping, frequently negatively. To ensure smooth transportation, to prepare ship crews, and to prevent unfortunate incidents as often as possible, a study of wind and wave factors is required. Studying how climate change may affect wind and wave conditions is a current global topic of interest to researchers, both in terms of simulation results for the past to determine how these parameters have changed over time, and for projections of their evolution for the near future. At the same time, increased concerns about the need to reduce greenhouse gas emissions have led to the need to find renewable resources. Capturing offshore wind energy by installing wind farms is increasingly common near port areas, thus providing the energy needed for them.

Another objective was to carry out a study of the wave and wind climate in European seas based on the most up-to-date data and along the main shipping routes. Based on wind speed information, it was also possible to carry out a study on wind farms installed, or in the process of being installed, in two high-traffic sea areas, namely the North Sea and the Mediterranean Sea.

Due to the variety of products that they can transit container ships are the most popular form of the transport vessel. For designers, understanding a container carrier's dynamics is crucial for both the hull and the waterways it travels on. Nowadays, container carriers are getting bigger and bigger and are required to sail faster and with more cargo, so it is important to find precise methods to achieve the desired characteristics. In addition, ships must abide by the requirement to limit pollution driven by marine transportation. New container ship designs with a wider bow entrance that can accommodate more containers have been made possible by an increase in the demand for transport capacity. To lessen total resistance, the vessel's hull needs to be optimized both fore and aft. Better environmental control and compliance with classification society regulations will result from increased ship efficiency. Consequently, an area of interest and developing research is the optimization of the hull shape, a topic that has been approached in the thesis for the case of a container ship, a type of vessel frequently encountered on European shipping routes.

In the design of vessels, assessing hydrodynamic performance is crucial. This gives the designer the ability to assess whether a design will satisfy the requirements. Although the idea of a ship's resistance is not new, the evolving specifications of container port vessels necessitate ongoing efforts to improve the prediction techniques of resistance. The ship's speed can be impacted by resistance, which could result in increased power and fuel needs.

Ship model testing in towing tanks has been a useful method for evaluating resistance (and sinking and trim) results up until now, more complex analysis is needed due to the growing requirement for precision, especially about wave resistance, and for obtaining faster results. Model testing is expensive because it demands for the precise building of a prototype vessel and the utilization of a test facility. The use of numerical simulations of models, where performance can be thoroughly assessed by computer simulations, can take the role of physical testing.

Partial differential equations can be used to quantitatively represent the complex issue of fluid flow. Due to their complexity, these equations hardly can be resolved analytically. The goal of computational fluid dynamics (CFD) is to find numerical answers to these equations. The partial differential equations must first be discretized to find a numerical solution. Following that, a group of algebraic equations are used to approximate the partial differential equations.

The advantages of CFD over conventional fluid flow experiments are numerous, but the most significant ones include relatively low cost compared to towing test, quick changes to the original design, or even complete changes, greater control over the experiment setup, and the ability to set conditions that might be challenging or impossible to achieve in a physical test.

In this context, a 1:135 scale model of a typical port-container ship was tested in the ETSIN-UPM test basin in Madrid and the results obtained were compared with the results of CFD analysis applied to the same ship. Therefore, it was also possible to perform an advantage/disadvantage analysis for each research method.

Outline of the thesis

In this thesis, an investigation of the characteristics of the European seas and the density of maritime traffic in these areas and their correlation with changes in wind and wave climate was proposed. Also, one of the most common types of transport vessels was studied to determine its operability in different scenarios. Thus, the thesis has been structured into 6 chapters, describing each problem investigated.

Chapter 1 presents the analysis of density maritime maps for the European seas and the specific features of each sea from a shipping point of view. The two main shipping channels in Europe, the Danube Black Sea Channel, and the Rhine Main Danube Channel were also analyzed.

In **Chapter 2** a statistical analysis of the goods transported in Europe is presented. The goods handled in each port, the types of goods transported, the types of vessels, the types of cargo, and the volumes of goods registered for containers were investigated. Based on these data, a ranking of the most popular ports for each category investigated was made. An analysis was also made of the accidents that occurred during the period studied.

Chapter 3 presents the wind and wave characteristics for these areas and along the main transport routes identified. As green energy is a new direction for Europe in the fight against pollution, wind farms in the North Sea and future wind farms in the Mediterranean Sea have been investigated.

In **Chapter 4** the results of the study on a container ship based on a series of numerical simulations are presented. Additionally, this study has been expanded to determine the additional wave resistance in **Chapter 5**, and towing tank tests have been used to validate the numerical simulations.

The findings of this study, individual contributions, suggestions for future research, and scientific publications elaborated during the studies that composed the thesis are presented in **Chapter 6**.

The doctoral thesis was carried out with the financial support of the project "Academic excellence and entrepreneurial values - scholarship system to ensure opportunities for training and development of entrepreneurial skills of doctoral and postdoctoral students - ANTREPRENORDOC", Contract no. 36355 / 23.05.2019 POCU / 380/6/13 - SMIS Code: 123847.

Terms and abbreviations

ABS	American Bureau of Shipping
BV	Bureau Veritas
CAMS	Copernicus Atmospheric Monitoring Service
CFD	Computational Fluid Dynamics
DJF	December, January, and February
DNV	Det Norske Veritas
DTC	Duisburg Test Case
EASM model	Explicit Algebraic Stress Model
ECMWF	European Centre for Medium-Range Weather Forecasts
EURO-CORDEX	European Domain-Coordinated Regional Climate Downscaling Experiment
EMODnet	European Marine Observation and Data Network
EMSA	European Maritime Safety Agency
ETSIN-UPM	Escuela Técnica Superior de Ingeniería de Montes, Universidad Politécnica de Madrid
IACS	International Association of Classification Societies
IFS	Integrated Forecast System
ISMT	Institute of Marine Technology, Ocean Engineering, and Transport Systems
JJA	June, July, and August
JONSWAP	Joint North Sea Wave Project
k-ω BSL model	k-ω Base-line model
k-ω SST model	k-ω Shear-Stress Transport
MAM	March, April, and May
PLA	Polylactic Acid
RANS	Reynolds-averaged Navier-Stokes equations
RAO	Response amplitude operator
RCP4.5	Representative Concentration Pathway 4.5
RO - RO	Roll On – Roll Off
SMHI	Swedish Meteorological and Hydrological Institute
SON	September, October, and November
UK	United Kingdom

WMO	World Meteorological Organization
Bwl	Waterline breadth
c_{aw}	Coefficient of the additional wave resistance
c_w	Coefficient of the wave resistance
Ct	Coefficient of total resistance
EFD	Experimental Fluid Dynamics
FFT	Fast Fourier transform
g	Gravitational acceleration
H	Wave height
Hs	Significant wave height
H/Lpp	Adimensional wave height
Lpp	Length between perpendiculars
PE	Percentage error
P_w	Wind Energy density
U_{10}	Wind speed at 10 m
U_{100}	Wind speed at 100 m
R_{aw}	Additional wave resistance
R_T	Total resistance
R_{Tc}	Calm resistance
R_{Tw}	Wave resistance
S_w	Wetted surface
SS	Sea State
Tm	Wave period
v	Ship speed
Vw	Wind speed
ρ	Water density
λ	Wave length
λ/Lpp	Adimensional wave length

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CHAPTER 1 – ANALYSIS OF THE MARINE TRAFFIC IN THE EUROPEAN SEAS AND THEIR MAIN FEATURES

1.1 Introduction

Freight and passenger transport grows with the economy, both in its upward and downward phases, like the COVID-19 pandemic and the 2008 global financial crisis, or the current conflict between Ukraine and Russia.

Europe is the continent with the most diversified transportation system in the world, occupying second place in the size of the road network and the railway network, respectively. The freight transport and passenger transport sectors are divided into nine pan-European transport corridors for better management and dynamics of freight flows.

Since ancient times, maritime transport has had traditions in the Mediterranean basin and later in the Atlantic countries. In Europe, we find both maritime and inland transport networks. In the last half-century, maritime transport has expanded in the European seas due to human development, increased trade, and exploitation of resources.

Europe is a major maritime hub in the world and controls about a third of the world's merchant fleet [1]. The maritime sector in this area is a globally competitive and efficient system, accounting for a third of international trade with four hundred million passengers embarking and disembarking in European ports every year [2].

The marine industry is vibrant and vital to connecting the European market with regional and global trading partners. [1][3].

However, in Europe, this mode of transport is growing year by year, with a few exceptions, as specified earlier, and according to the "*European Maritime Transport Environmental Report"*, in 2018 compared to 2017, there were 5.3% more passengers boarding and landing, and during that same time, the overall gross weight of cargo grew by 3.2%.

On these grounds, it was necessary to investigate the current characteristics of maritime areas in Europe, and the seas and canals that are examined in this thesis and presented in Table 1.1.

Table 1.1 Case study

Seas	
Caspian Sea	Irish Sea
Azov Sea	North Sea
Black Sea	Baltic Sea
Sea of Marmara	Norwegian Sea
Mediterranean Sea (and its divisions)	Barents Sea
English Channel	White Sea
Celtic Sea	
Channels	
The Danube-Black Sea Channel	The Rhine-Main-Danube Channel

In the following sub-chapters, the maritime areas of Europe have been studied, as well as the main channels, the Danube-Black Sea Channel, and the Rhine-Main-Danube Channel, which link inland navigation and maritime navigation.

An analysis of the characteristics of each sea was carried out, as well as a study of maritime traffic and the types of ships encountered in each zone. Finally, this study's conclusions and the directions followed for this thesis were listed.

1.2 Black Sea, Azov Sea, and Sea of Marmara

Map of Density generated from Marine Traffic [4] for the year 2021, which can be seen in Figure 1.1, outlines the main routes in this area. An important factor in increasing maritime traffic density is the quantity of oil transported from Central Asia to the Russian port, Novorossiysk [5], and from this port to the other main routes.

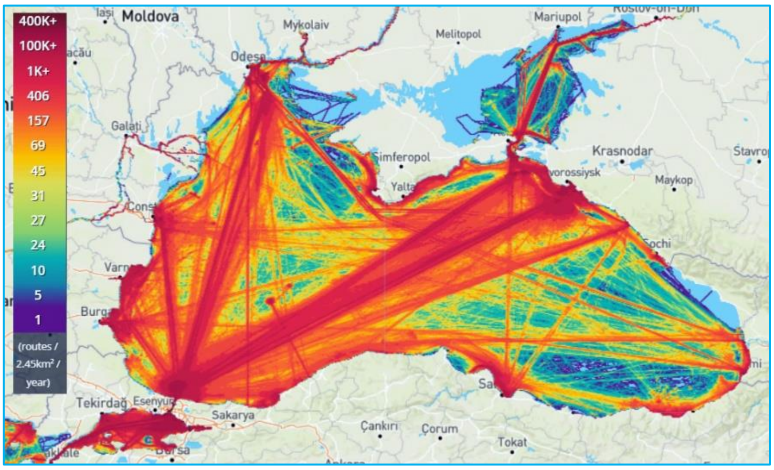


Figure 1.1 Marine Traffic Density Map in the Azov Sea, the Black Sea, and the Sea of Marmara for the 2021 year [4]

Navigation takes place inside the Black Sea through ports (Constanta, Varna, Novorossiysk, Trabzon, Samsun, Eregli, Odesa, Batumi) and outside the Black Sea through the strait of Turkey. The main exit route from the Black Sea to the Ocean is through the Aegean Sea and the Mediterranean Sea.

The main types of ships found in this area were identified based on information extracted from Marine Traffic [4]. As can be observed in Figure 1.2, we find bulk carriers, oil tankers, passenger ships, cruise ships, ferries, fishing vessels, Ro-Ro type vessels, and tugs.

More than half of the Black Sea ships are cargo and oil tankers. During the summer there is an increase in transport by cruise ships and ferries for tourist purposes.

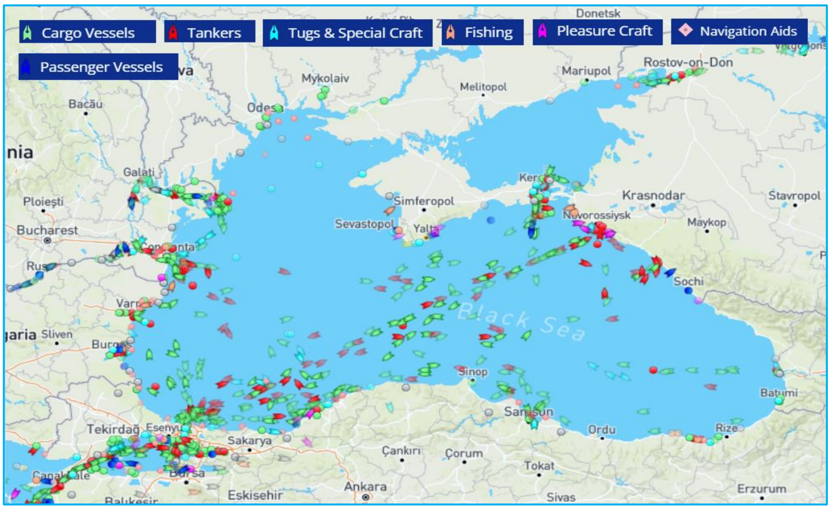
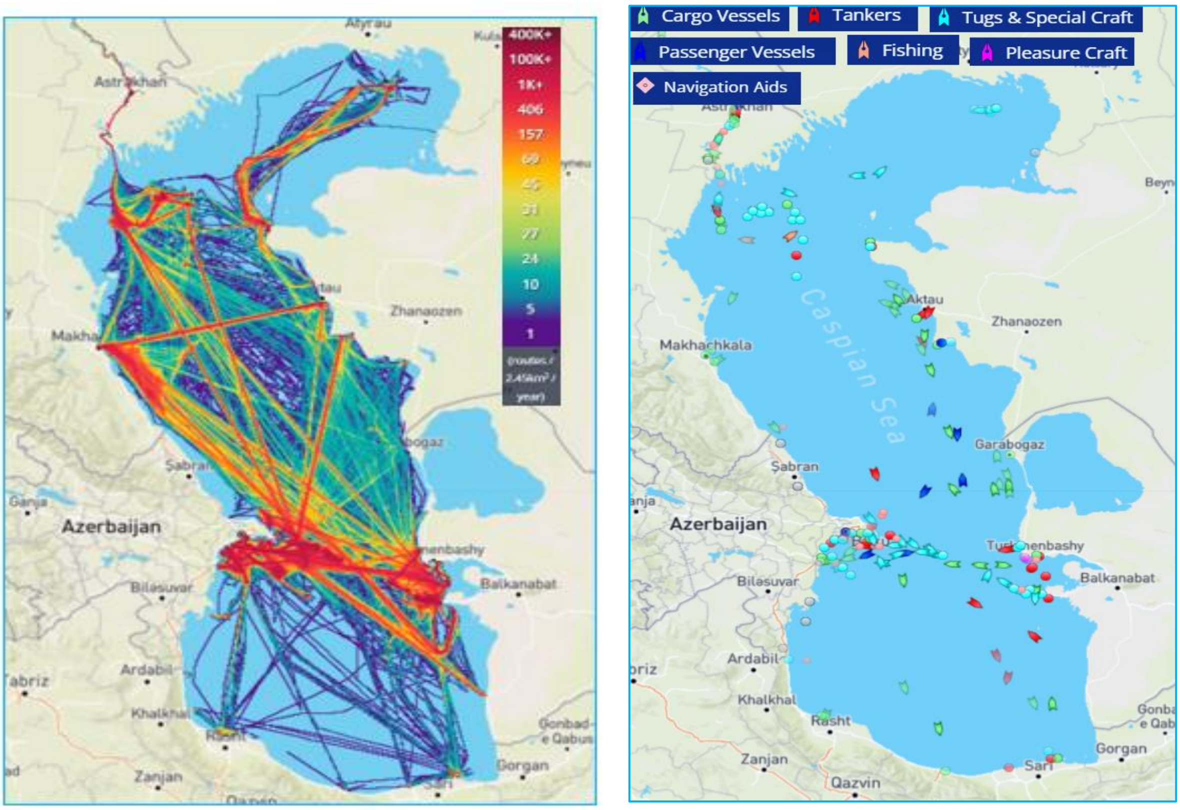


Figure 1.2 Types of ships in the Azov Sea, the Black Sea, and the Sea of Marmara, June 2022 [4]

1.3 The Caspian Sea

The principal shipping lanes in the Caspian Sea (Figure 1.3) are Baku - Aktau, Baku – Turkmenbashi, and Mahacicala - Aktau. Fishing is highly developed and over 90% of the world's sturgeon reserves are found in this area.

Maritime transport has long been used in the Caspian Sea for the transport of all goods, but today it is used mainly for the transport of natural resources. The Trans-Caspian Transport Corridor [6][7] is one of the most important silk transport routes, connecting China, Kazakhstan, Azerbaijan, Georgia, Turkey, and Europe.



(a) (b)

Figure 1.3 Marine Traffic Density Map (a) and types of ships (b) in the Caspian Sea [4]

In the future, freight transport through the Caspian Sea will develop more and more because it is one of the most important routes between China and Europe.

1.4 The Mediterranean Sea

The Mediterranean Sea is a representative area for maritime traffic (Figure 1.4), the third-largest commercial transport in the world, and oil from the Middle East to Europe and North America is transported by a large number of oil tankers that travel on the major routes.

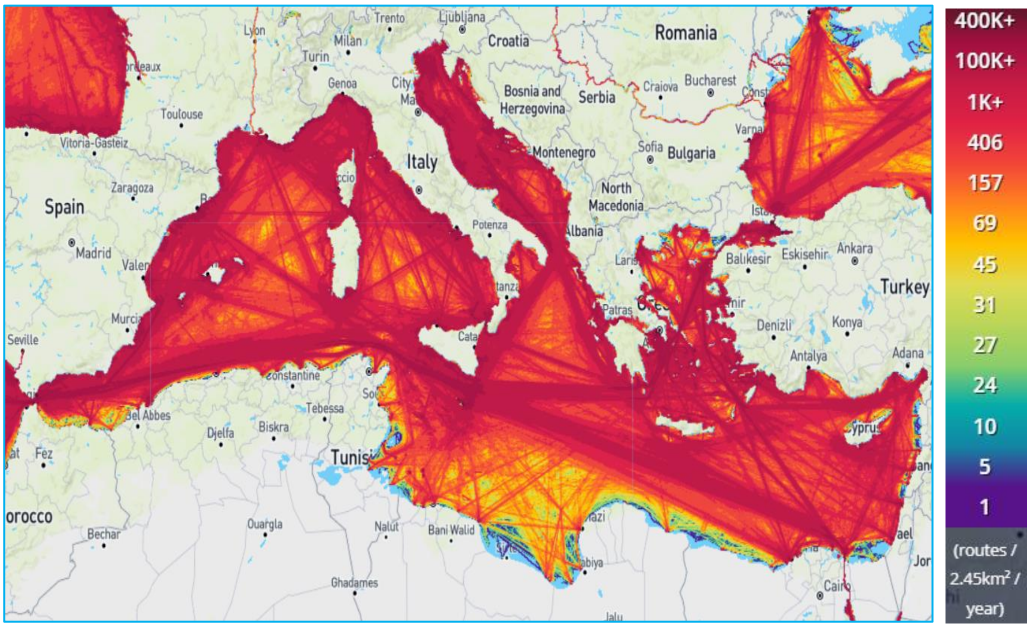


Figure 1.4 Traffic Density in the Mediterranean Sea for the 2021 year [4]

In this area, maritime traffic is also developed through passenger ships due to the high tourist potential. Ever since the Suez Canal was opened in 1869, the Mediterranean Sea has served as a trans-national commerce route. [8].

Ships crossing the Mediterranean Sea waters (Figure 1.5) are cargo, tanks, passenger ships, ferries, fishing vessels, high-speed boats, yachts, and even military vessels.

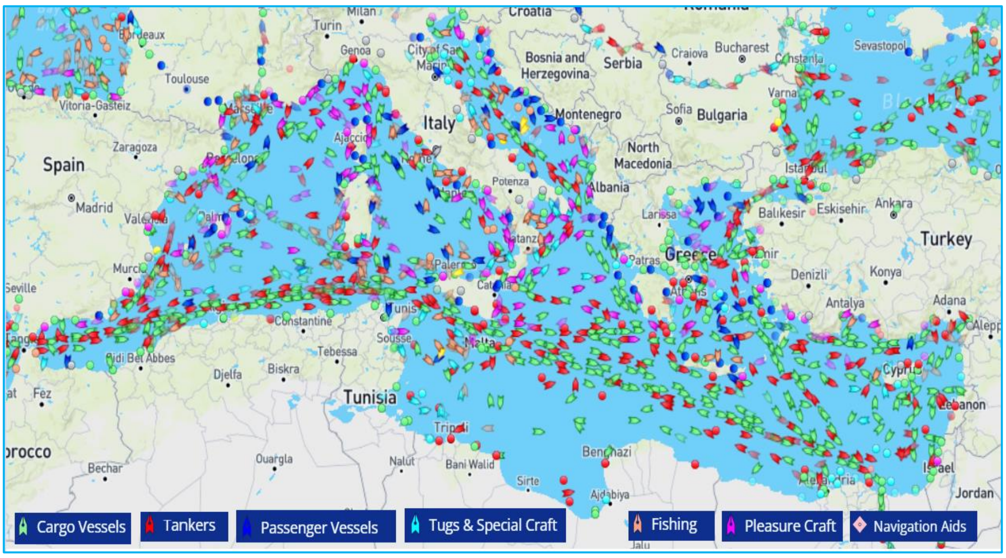


Figure 1.5 Types of ships in the Mediterranean Sea, June 2022 [4]

1.5 The English Channel

The English Channel is one of the busiest regions (Figure 1.6) in the world in terms of maritime transport. The main routes are Great Britain-Europe and the North Sea-Atlantic Ocean.

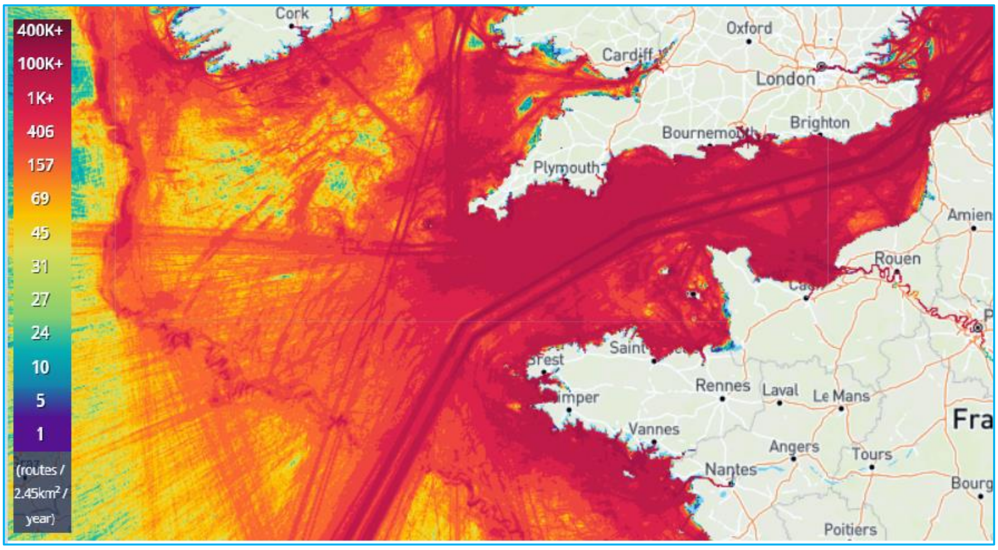


Figure 1.6 Marine Traffic Density Map in the English Channel for the 2021 year [4]

Tourism in the English Channel has traditions dating back to the 19th century and has continued to develop to the present day, which is why we see many pleasure boats and ferries (Figure 1.7). In the English Channel, there is a wide range of ferry routes to the ports of Dover, Calais, Dunkirk, Newhaven, Plymouth, Poole, Cherbourg, Portsmouth, Le Havre, Saint-Malo, Weymouth, and many more.

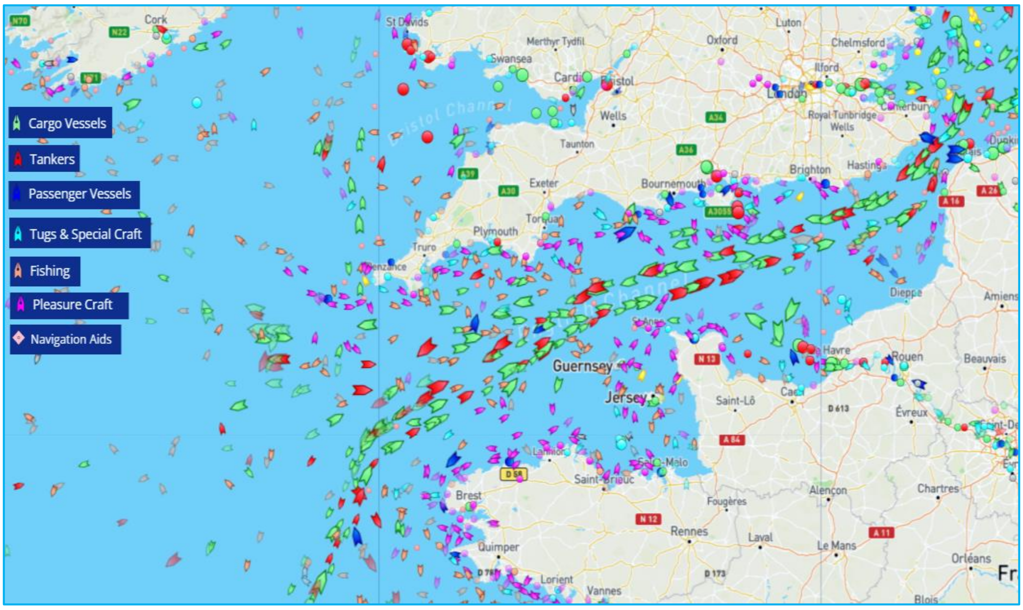


Figure 1.7 Types of ships in the English Channel, June 2022 [4]

1.6 The Celtic Sea

Figure 1.8 shows traffic in the Celtic Sea area. The densest area is the one connecting the English Channel and the St George's Channel.

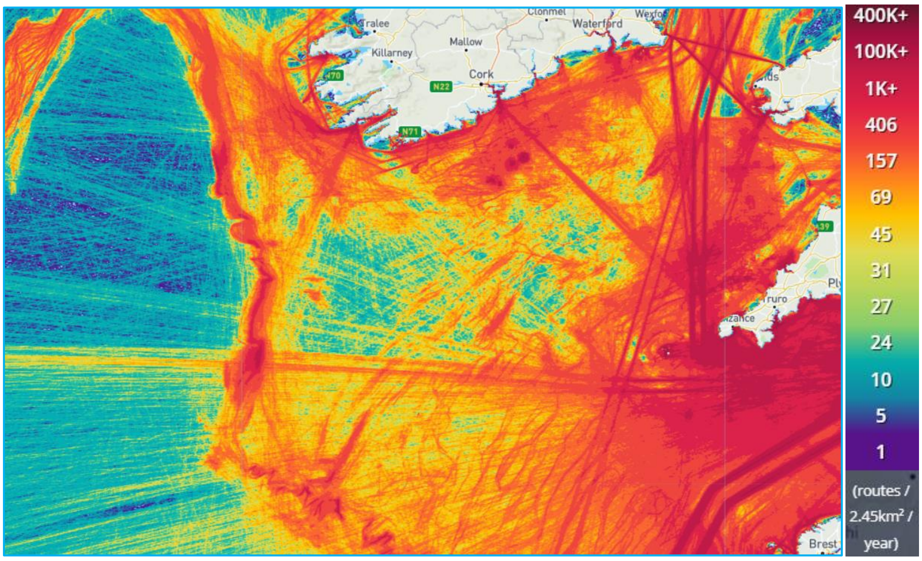


Figure 1.8 Traffic Density in the Celtic Sea for the 2021 year [4]

In the coastal areas, there is a varied tourist industry, as can be seen in Figure 1.9, which show the types of vessels that cross the Celtic Sea. The main types of vessels found in this area are cargo vessels, fishing vessels, and leisure craft.

The Celtic Sea has a well-developed fishing industry, fishing approximately 2 million tons annually as of 2007. Aquaculture has progressed over the last 20 years and has diversified as much as possible.

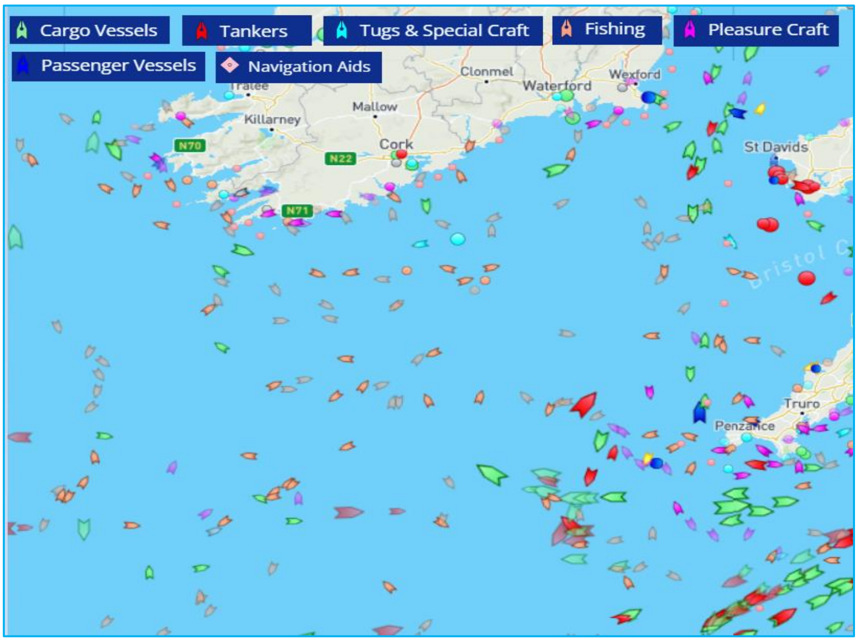
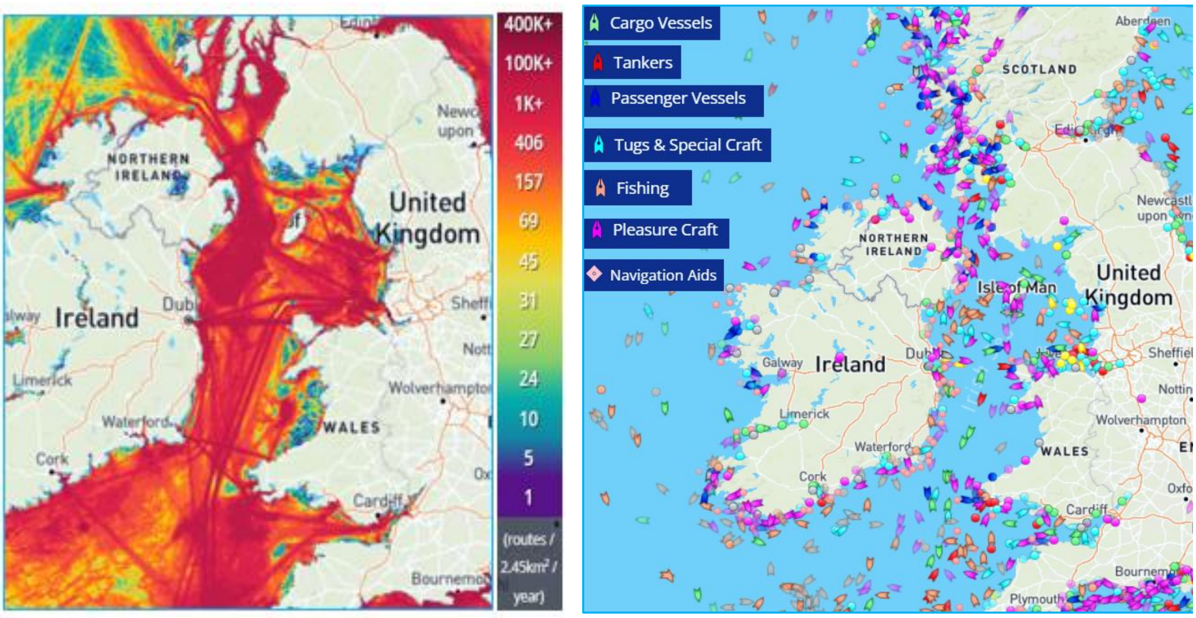


Figure 1.9 Types of ships in the Celtic Sea, June 2022 [4]

1.7 The Irish Sea

The traffic in the Irish Sea (Figure 1.10) area is quite high. Millions of passenger ships and millions of cargo ships run annually.

The largest maritime traffic is found on the route connecting Ireland to Great Britain and in the area the ports of the big cities positioned on the coast: Dublin, Liverpool, Holyhead, Belfast, Southport, Blackpool, Bangor, and Crosby.



(a) (b)

Figure 1.10 Marine Traffic Density Map (a) and types of ships (b) in the Irish Sea [4]

Due to pollution in recent years, the fishing industry has been affected. However, Fleetwood Harbor remains the main fishing port, along with Ardglass, Kilkeel, and Mornington, and the main types of fish caught are herring and whiting.

Also, in this area are located a series of offshore oil platforms and natural gas platforms. Several ferries connect most ports in the Irish Sea. The largest ferry in the world operates in this area, on the route Dublin - Holyhead. Another important route connects Great Britain to Ireland.

1.8 North Sea

The North Sea, as can be seen in Figure 1.11, is the meeting place of important European routes, and a major fishing area, especially in the south. The most widely used artificial waterway in the world is the canal that connects the North Sea to the Baltic Sea, called Kiel Canal.

If we refer to maritime transport, in this area are located the most crowded and important ports in the world: Rotterdam (ranks first in Europe and tenth internationally in the first half of 2022 [9]), Antwerp, Hamburg, Valencia, and Bremen. In terms of Ro/Ro transport, the important port in Europe is Bruges-Zeebrugge.

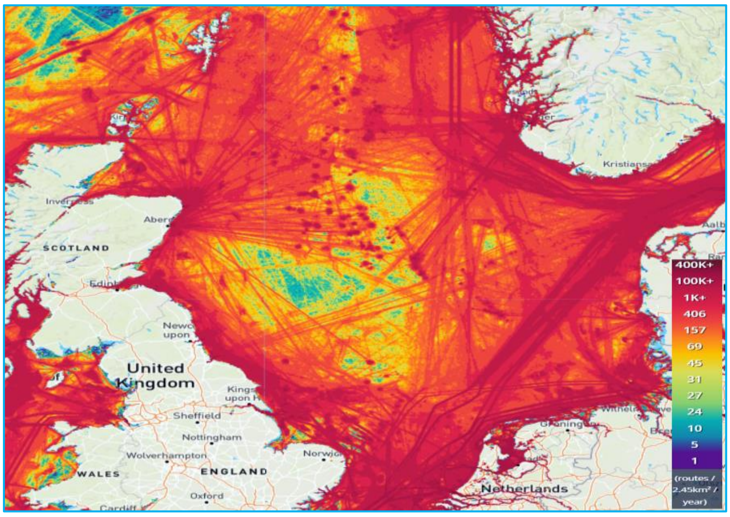


Figure 1.11 Traffic Density in the North Sea for the 2021 year [4]

In the North Sea, we find a wide variety of types of ships [10] (presented in Figure 1.12): transport ships, fishing boats, offshore boats, sports boats, special boats as well as passenger ships. The connection between the United Kingdom and the North Sea is made by ferries.

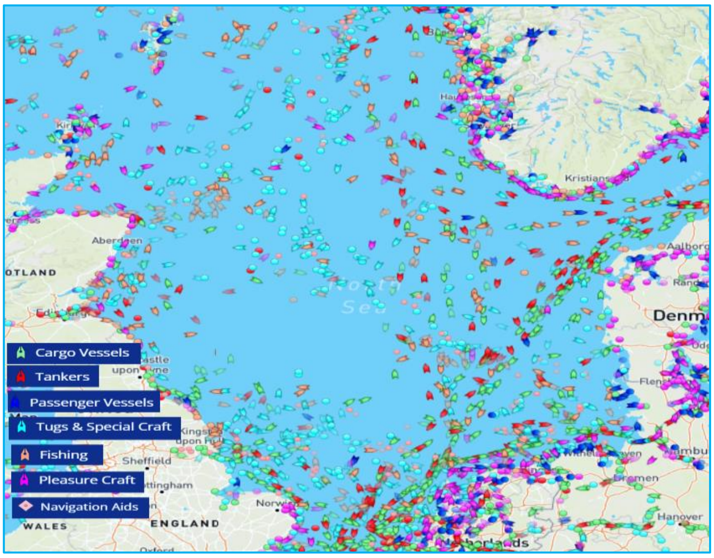


Figure 1.12 Types of ships in the North Sea, June 2022 [4]

1.9 Baltic Sea

Maritime traffic density and dynamics (Figure 1.13) are influenced by transport demands, which are directly proportional to economic growth [11]. There are almost four hundred seaports in the Baltic Sea and nine dozen of them are of international importance.

Due to the ice, narrow straits, the presence of islands, and shallow waters, the Baltic Sea is considered a difficult area for navigation. However, before the war between Russia and Ukraine, the density of maritime traffic was increasing, especially for cargo ships operating on routes to Northern Europe and Russia. Other busiest areas in terms of maritime navigation are the Gulf of Finland and the Danish Straits.

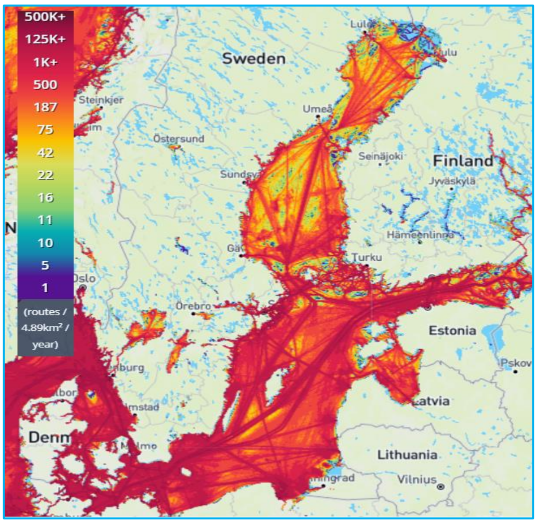


Figure 1.13 Marine Traffic Density Map in the Baltic Sea for the 2021 year [4]

The three main types of ships sailing in the Baltic Sea are cargo ships, container ships, and ferries. Of all ship types, shown in Figure 1.14, more than 50% are cargo ships, 20% are tanks, and 11% are passenger ships [12]. The beautiful cities, and the lack of typhoons and tides, make the Baltic Sea a suitable area for cruise ships, pleasure crafts, boats, or even kayaks.

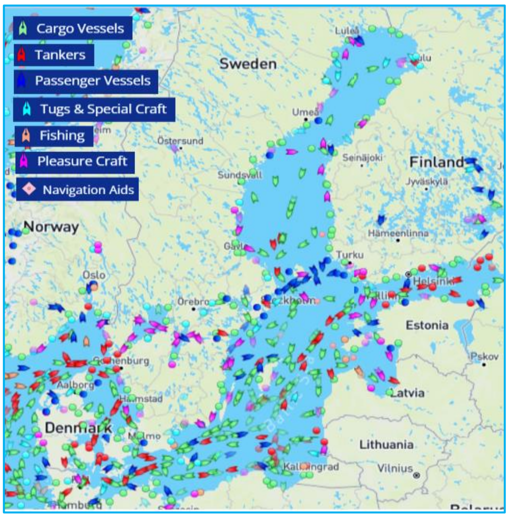


Figure 1.14 Types of ships in the Baltic Sea, June 2022 [4]

1.10 Norwegian Sea

Norway is one of the European countries with a complete maritime cluster, being the third largest shipping country in terms of cargo size and among the top ten countries in terms of annual cargo carried. The density of maritime traffic can be observed in Figure 1.15. In the coastal area, the density of maritime traffic is the highest.

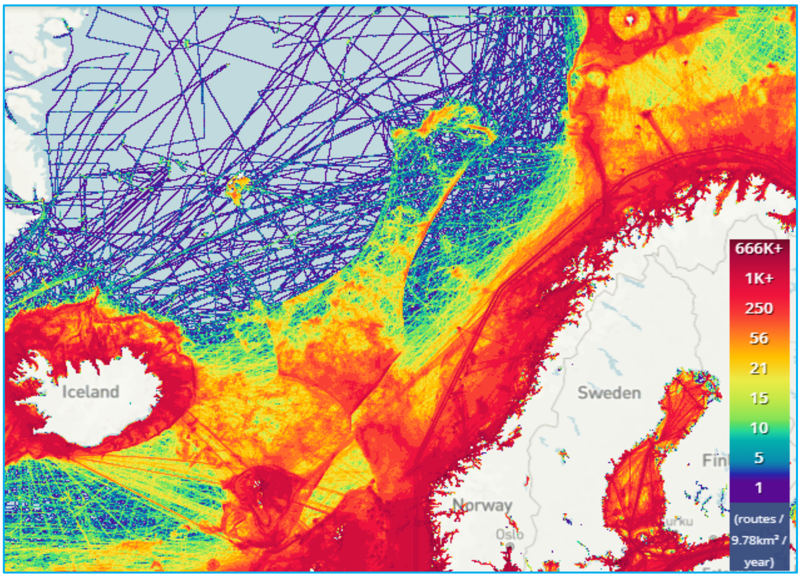


Figure 1.15 Traffic Density in the Norwegian Sea for the 2021 year [4]

The types of ships located in the Norwegian Sea can be viewed in Figure 1.16. In the coastal area, there are many schools of fish, the most important species being the herring. The seabed is rich in oil and natural gas deposits, which favors commercial exploitation.

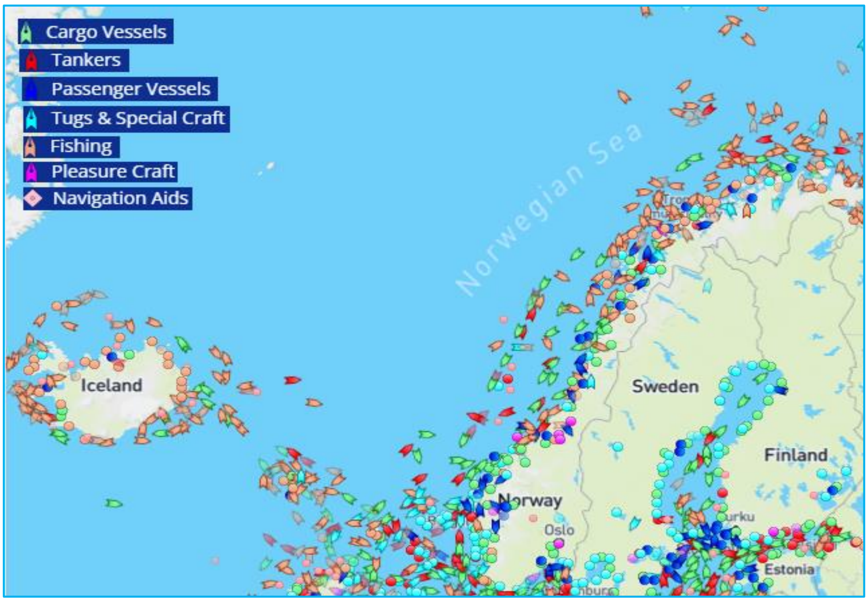


Figure 1.16 Types of ships in the Norwegian Sea, June 2022 [4]

1.11 Barents Sea

Figure 1.17 shows maritime traffic in the Barents Sea. The two major ports are Murmansk and Vardø. The amount of maritime traffic has increased near the coast.

The Barents Sea hosts many shipping activities [13], such as coal transport, coastal passenger, and cargo traffic along the Norwegian coast, as well as cruise ships carrying tourists to the North Cape, Svalbard in Franz Josef Land.

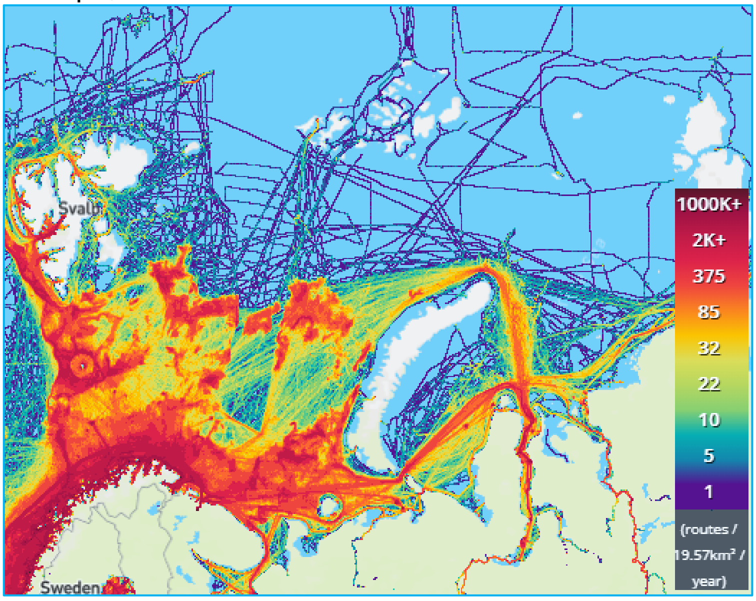


Figure 1.17 Traffic Density in the Barents Sea for the 2021 year [4]

Ships crossing the Barents Sea are shown in Figure 1.18. The Barents Sea has a relatively developed fishing industry, containing the largest remaining cod population in the world, as well as significant stocks of haddock and capelin. As in the Norwegian Sea, large oil deposits are also found here.

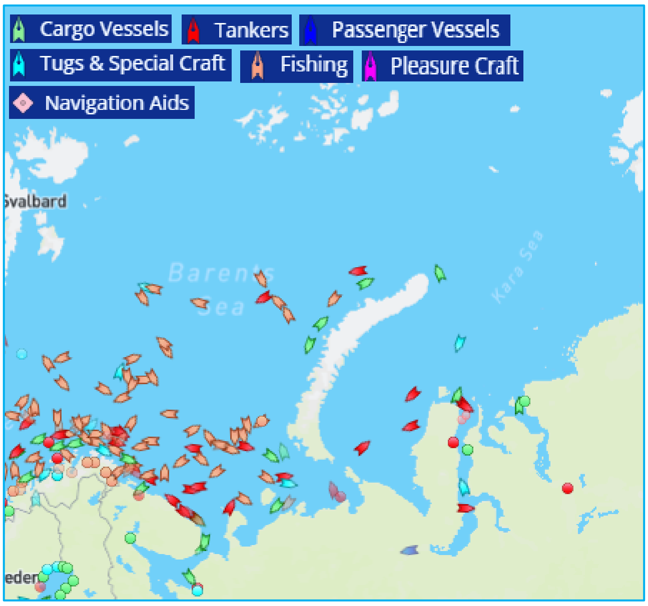


Figure 1.18 Types of ships in the Barents Sea, June 2022 [4]

1.12 White Sea

Maritime traffic is outlined in Figure 1.19. An important sea route is the White Sea-Baltic Sea Canal, which connects the Baltic Sea to the White Sea. The most developed port in the White Sea is Arkhangelsk, together with Mezen, Belomorsk, Kem, Kandalaksha, Onega, and Umba.

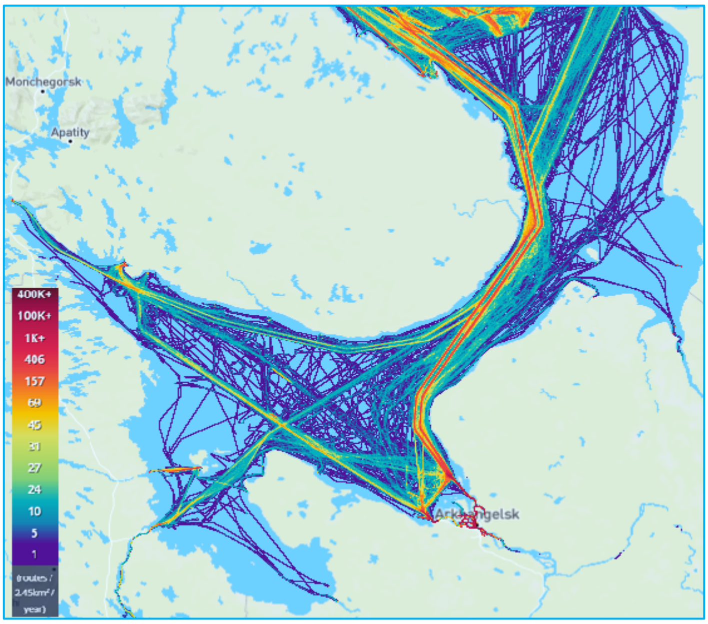


Figure 1.19 Marine Traffic Density Map in the White Sea for the 2021 year [4]

The White Sea has a long history when it comes to ships because it was a significant Soviet navy and submarine base in the contemporary age. Today we do not find many ships in this area, as can be seen in Figure 1.20. Although the White Sea tends to freeze over, this does not affect ships due to the use of icebreakers.

Figure 1.20 Types of ships in the White Sea, June 2022 [4]

1.13 The Danube-Black Sea channel

The Danube runs in Central and Eastern Europe and is an important river in Europe, crossing ten countries and four capitals [14]. In terms of length, it is the second biggest river in Europe, after the Volga, and stretches about 2.845 km [15], after which it flows into the Black Sea. The Black Sea is connected by the Kerch Strait to the Azov Sea, by the Dardanelles to the Aegean Sea, and by the Bosphorus Strait to the Sea of Marmara.

The Danube-Black Sea Canal, the third longest channel after the Suez Channel and the Panama Channel, consists of two branches: the main branch, in use since May 1984 and linking the Port of Constanta to the Port of Cernavoda, and the northern branch, in use since October 1987 and linking the Navodari Channel to the Poarta Alba Channel.

The need for a channel connecting the Danube to the Black Sea was mainly to shorten the distance and therefore the time for the movement of goods, but also because of navigation limitations on the main arms of the Danube.

Freight transport through the channel is a cheaper alternative to road, rail, or air transport and facilitates Black Sea trade with Asia and the Middle East. Shipping in this area ([14], [16]) has several disadvantages, such as reduced transport speed, changing waterway conditions, and the need to upgrade the fleet and port infrastructure. Nevertheless, there are several advantages, such as safety, low transport costs, the ability to transport large quantities of goods, and environmental sustainability compared to other transport methods.

The types of vessels [17] encountered are self-propelled boats, pushed convoys, tugboats, and push barges are the most common types, which are the most methodical in terms of price and quantity transported. The development of canal traffic in terms of vessel capacity for the period 2000-2022 has been investigated based on information obtained from the Waterways Administration (ACN) [18]. A similar analysis has been performed for cargo handled in Figure 1.21.

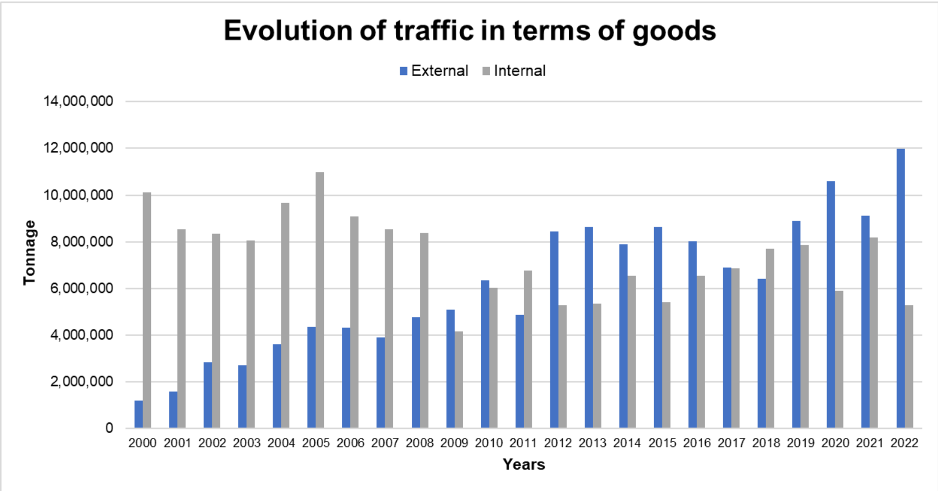


Figure 1.21 Evolution of traffic in terms of goods handled

During the whole period under review, 310 548 993 tonnes of cargo were handled on the Danube-Black Sea Canal, of which 45% were external and 55% were internal. While in the period 2000 to 2008, the percentage is higher for internal traffic, from 2009 to 2022 the difference between internal and external has adjusted, with the number being similar, which shows that trade has improved, both for export and import.

1.14 The Rhine-Main-Danube channel

Another important channel for navigation is the Rhine-Main-Danube Channel, which connects the Black Sea and the North Sea for 30 years via the Rhine, Main, Danube, and the Danube-Black Sea Canal.

The Danube-Main-Rhine Canal facilitates trade for all the Danube countries, and northern European countries can access the Mediterranean through the Bosphorus-Dardanelles route much faster than through Gibraltar. In the 24-hour mode of operation, ships can cover the Rotterdam-Constanta distance in about 11 days and 14 hours in case of regular sailing conditions, according to Danube Logistics Portal [19].

The channel is navigable all year round, except when the water level is too low, and there are 16 locks across the canal, operated by remote control points, with an infrastructure upgraded 10 years ago, and most of them designed to save water.

Freight traffic on the Rhine-Main-Danube Channel has been studied in terms of goods transported by area (Figure 1.22), by vessel type, and by type of goods for the period 2010-2020 [20], based on data provided by Eurostat [1].

The international pandemic situation caused by the Covid-19 virus and the war between Russia and Ukraine have had negative effects on freight transport, but the industry continues to thrive even in difficult times. The most popular goods are food, feed, agricultural and forestry products, minerals, iron, steel, and non-ferrous metals.

A total of 9 187 079 thousand tonnes were transported between 2010 and 2020. In terms of countries, the Netherlands handled the largest share of the total number of tonnes of freight, 43%, followed by Germany at a difference of 1 528 981 thousand tonnes and Belgium at a difference of 1 967 000 thousand tonnes.

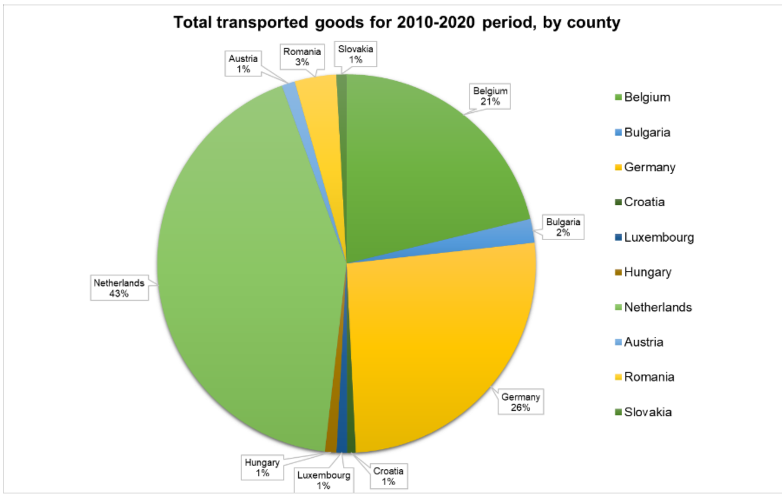


Figure 1.22 Total goods handled by zone

In terms of vessel types used on the Rhine-Main-Danube Channel, self-propelled barges, un-propelled barges, self-propelled tanker barges, and un-propelled tanker barges were investigated. Of the total of 8 983 955 vessels, 51.84% were self-propelled barges, 26.23% were self-propelled tanker barges, 21.13% were un-propelled barges, and 0.8% were un-propelled tanker barges. The Netherlands remains in first place for all four ship types, and Germany and Belgium remain in the top 3, for all ship types except non-self-propelled barges, where Romania ranks 3rd, overtaking Belgium with 68 138 ships. Metal ores and other mining products were the most carried goods, followed by coke and refined petroleum products.

1.15 Conclusions

The maritime sector of the European seas is of major importance to the economies of the countries through which they pass, with a tradition dating back to ancient times. This sector relates to inland navigation, which is an equally advantageous method of transporting goods.

These two types of transport are constantly evolving as a reflection of growing market demands, but also because of the many advantages they offer and the affordable prices of the services.

In this chapter, each of Europe's seas and the two main waterways, the Danube-Black Sea Channel, and the Rhine-Danube-Main Channel have been reviewed in terms of maritime traffic. The particularities of each area were also presented.

The most important seas for maritime transport are the Mediterranean Sea, which links Europe, Asia, and Africa, the North Sea, where Europe's most important ports for cargo transport are located, and the Black Sea, which lies between Asia and Europe.

The infrastructure and port fleet must be improved in order to expand cargo traffic on the Rhine-Main-Danube Canal, which includes the Danube-Black Sea Canal. The Rhine-Main-Danube Canal, an important freight route connecting the North Sea to the Black Sea, has the best possibility of continuing to play a large role in European transportation given the number of cities it passes through.

In conclusion, maritime traffic in the areas studied is increasing and, although it is the slowest mode of transport, maritime transport has a certain range of characteristics that make it the most used mode of transport.

The research presented in this chapter is an extended and updated version of the originally published articles:

1. **Chiroşcă Ana-Maria**, Rusu Liliana, 2021. The Characteristics of the North Sea and its Importance for Maritime Transport, AUDOE, Vol. 17, No. 6/2021, pp. 224-229, ISSN: 2065-0175, https://dj.univ-danubius.ro/index.php/AUDOE/article/view/1481
2. **Chiroşcă Ana-Maria**, Rusu Liliana, 2021. Statistical and Economic Analysis of the Rhine-Main-Danube Canal, the Bridge Between the North Sea and the Black Sea, Journal of Danubian Studies and Research, Vol. 11, No. 1/2021, pp. 184-191, ISSN 2284-5224, https://dj.univ-danubius.ro/index.php/JDSR/article/view/1288/1491.
3. **Chiroşcă Ana-Maria**, Rusu Liliana, 2021. Study on Navigation Conditions and Shipping Traffic on the Danube in the Period 2010-2020, Journal of Danubian Studies and Research, Vol. 11, No. 1/2021, pp. 192-201, ISSN 2284-5224, https://dj.univ-danubius.ro/index.php/JDSR/article/view/1301/1490
4. **Chiroşcă Ana-Maria**, Rusu Liliana, 2021. The Economic Importance of Navigation Along the Danube-Black Sea Channel, presented at XXIth International Multidisciplinary Scientific GeoConference Surveying, Geology and Mining, Ecology, and Management – SGEM 2021, 14-22 August, Albena, Bulgaria, Volume 21, 3.1, pages 297-306. https://doi.org/10.5593/sgem2021/3.1/s12.45 (indexed Scopus)
5. Vazdoaga, I., **Chirosca**, A., Rusu, L., Popa, V. -I., 2020. Extreme phenomena on Danube hydrodynamics and the influence on the navigation conditions, 20th International Multidisciplinary Scientific GeoConference SGEM 2020, 18 - 24 August 2020, Vol. 20, 123-130, ISBN:978-619-7603-08-8 https://doi.org/10.5593/sgem2020/3.1/s12.016 (indexed Scopus)
6. **Chiroșcă Ana-Maria**, Rusu Liliana, 2020. Sea state characteristics and the maritime traffic in the European seas, 20th International Multidisciplinary Scientific GeoConference SGEM, 18 - 24 August, Vol. 20, 1314-2704, ISBN:978-619-7603-08-8, https://doi.org/10.5593/sgem2020/3.1/s15.111 (indexat Scopus)
7. **Chiroşcă Ana-Maria**, Rusu Liliana, 2019. Marine Traffic on Mediterranean Seas and its divisions, Mechanical Testing and Diagnosis, Volume 4, pp. 11-18, ISSN 2247 – 9635, 2019 (IX) https://doi.org/10.35219/mtd.2019.4.02

CHAPTER 2 – STATISTICAL ANALYSIS OF SHIPS AND GOODS TRANSPORTED IN THE EUROPEAN SEAS

2.1 Introduction

In the European sea area, freight and passenger transport is a key element of the economy, both internally and externally with other continents. The most developed area for this industry is the ports, which show increases in the volume of goods transported and the number of passengers per year ([21] to [23]), with small exceptions when there are more difficult periods (economic crisis [24], coronavirus pandemic (COVID-19) [21], war between Russia and Ukraine [25]), but which recover quickly.

There are many important ports in Europe, connecting not only to other seas but also to other rivers. Many of the routes from these ports connect to the rest of the continents [26], such as the North Sea to America and the Mediterranean Sea to Asia.

A statistical analysis of the density of maritime traffic, the types of ships, and the problems they face, for each subdivision of the European seas, has been studied and presented in this chapter for a period of ten years. The result of the statistical analysis, based on information provided by Eurostat [1], for each category is presented in detail in the following subchapters.

2.2 Goods handled in all ports

Freight trade is one of the most exploited maritime sectors and for this reason, "mega-ships" ([27], [28]) have been built to carry larger cargo on a single route. Between 2010 and 2019, an average of about 4 468 767 thousand tonnes were transported annually, of which 59% represents domestic trade within Europe and the remaining 41% trade with the rest of the world. Figure 2.1, shown below, shows that the highest number of thousand tonnes were found in the Netherlands at 12.91%, followed by the United Kingdom at 11.12%, Italy at 10.69%, Spain at 9.86%, and Turkey at 9.10%.

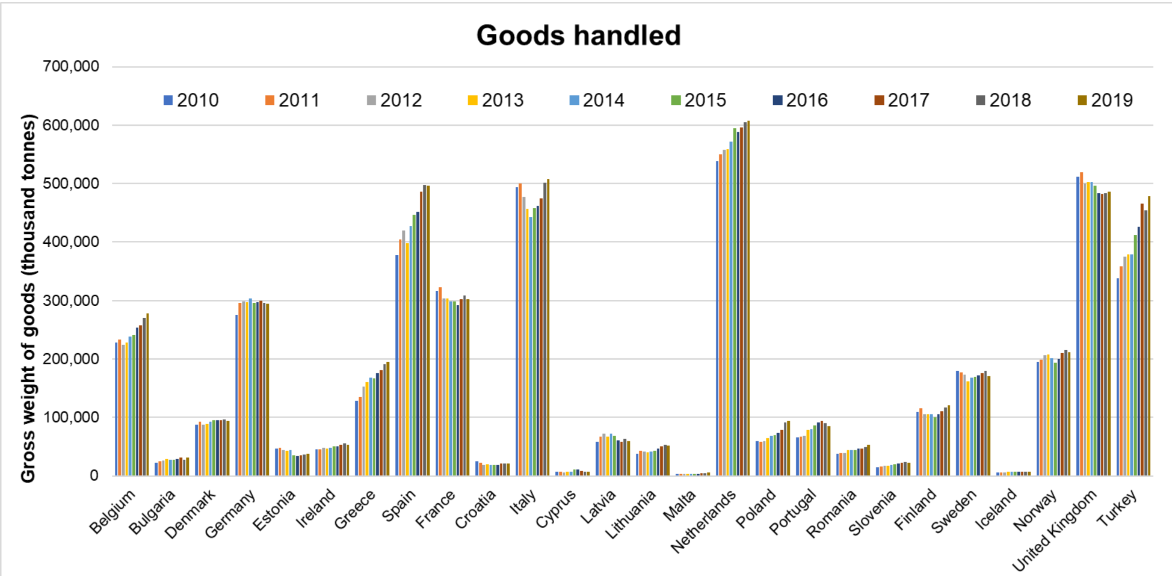


Figure 2.1 Goods handled in all countries, by year

2.3 Cargo types

All types of cargo are transported in Europe, but the main types can be divided into the following categories: liquid bulk, dry bulk, large containers, and container vessels. Of the total goods transported, 37.8% were liquid bulk goods, 25% were dry bulk goods, 20.4% were large containers, and the other types had much smaller values, accounting for no more than 6% of the total. The main categories according to the percentages recorded by each country are listed in Figure 2.2.

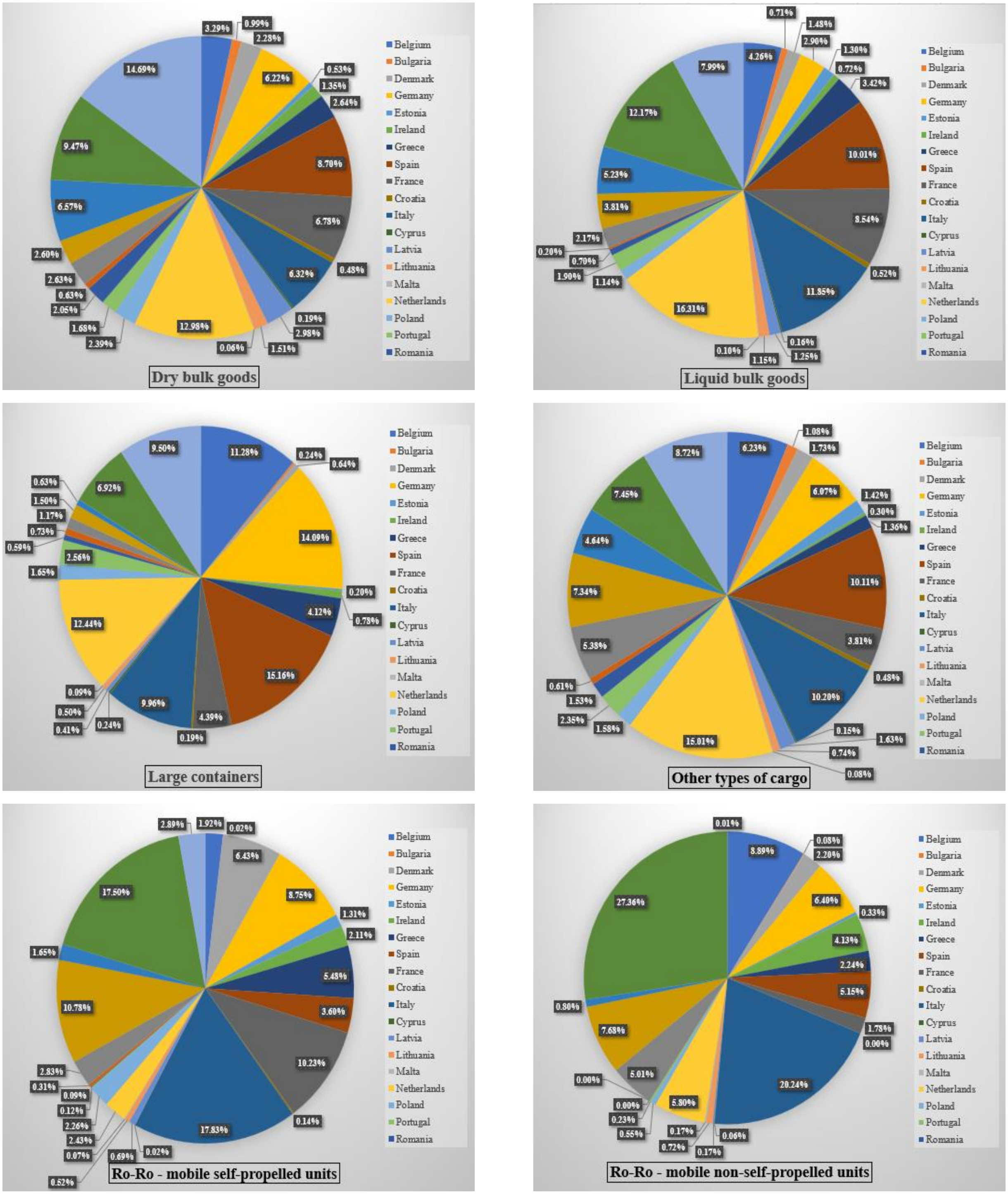


Figure 2.2 Main types of cargo

2.4 Good types

The manner of transportation and the nature of the products being transported are strongly related. Today, thanks to the multitude of ship types, any type of cargo can be transported, from natural gas, oil, minerals, metals, textiles, machinery, and tools, to food, live animals, and other categories [29]. The categories of goods that were transported most often during the reference period are presented in Figure 2.3

During the 10 years, 2,129,884 thousand tonnes of agricultural, forestry, and similar products were transported. Spain controls 20.6% of this type of goods, followed by Germany and the Netherlands, both with 10%. Food products were transported 20% less than agricultural products, with Spain still in the first place, but this time with a higher percentage, 36.7%, followed by the Netherlands with 19% and Germany with 11.5%. The same top 3 countries are also registered for wood and wood products, except furniture.

The most goods, with a total of 8,594,094, are coal, crude oil, and natural gas. After these are coke and refined petroleum products, with 7,598,248 thousand tonnes recorded.

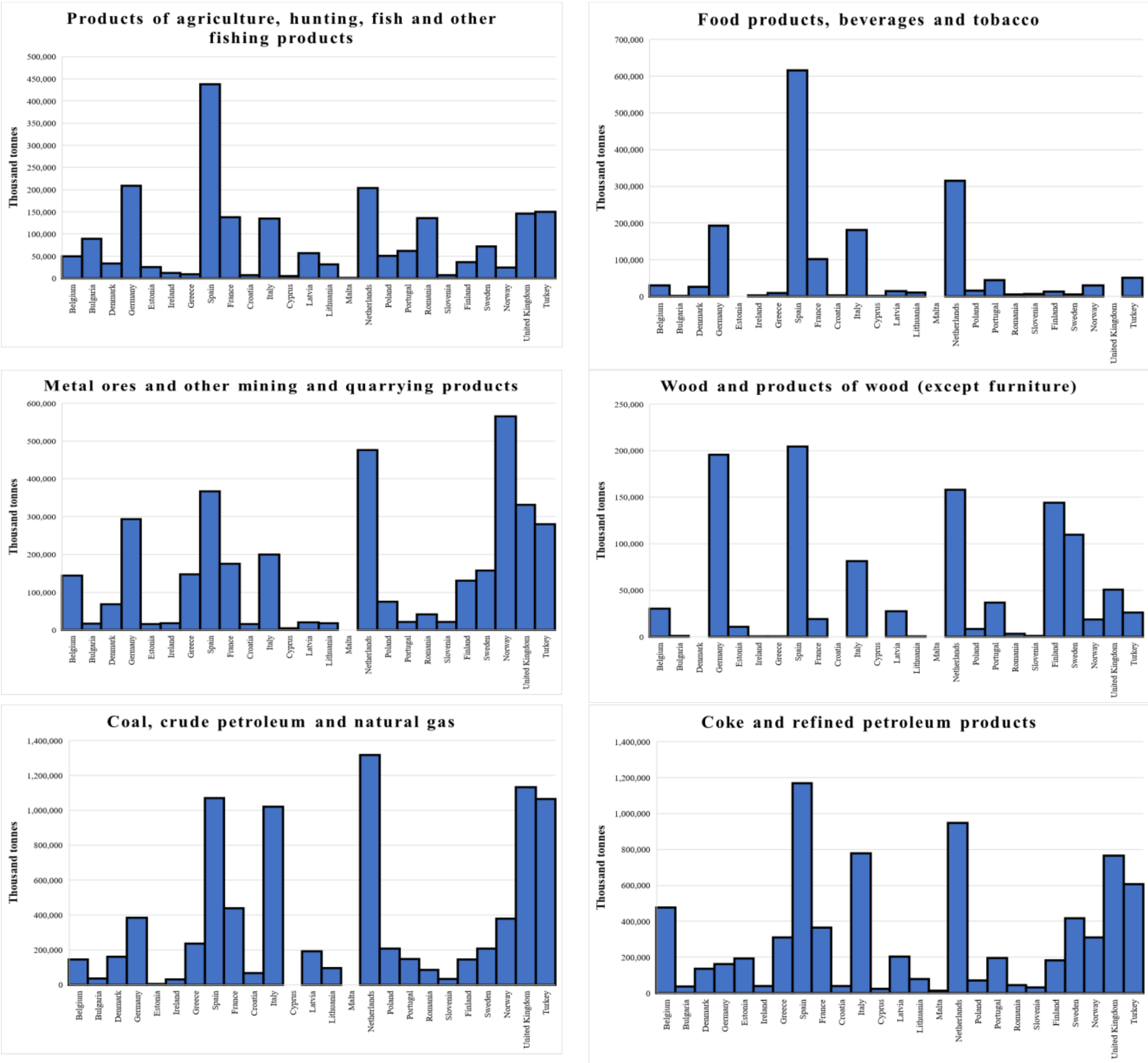


Figure 2.3 Main types of good

2.5 Vessel types

As long as such a diverse range of goods are transported in Europe, there are dedicated types of vessels for each to carry them, such as general cargo vessels, liquid bulk tankers, dry bulk vessels, container vessels, barges, tugs, and pushers. Other categories of vessels are passenger ships, cruise ships, and yachts. There are also vessels used for maritime activities, such as research vessels, offshore vessels, fishing vessels, and other similar vessels.

Figure 2.4 shows the percentages for vessels by type for the reference period. General cargo ships dominate the European shipping industry, accounting for 15 893 542 of the 23 321 274 ships encountered over the period 2010-2019. Greece, Italy, and Denmark dominate this sector in similar proportions.

The second most popular category of ships for the European area is passenger ships, from which cruise ships have been drawn. No less than 3,558,045 ships sailed during this period, most of them in Croatia, Greece, and Spain. The number of cruise ships is increasing year after year and is becoming a favorite way to relax and explore as many destinations as possible in as short a time as possible, with Italy, Greece, and Spain being the most common destinations.

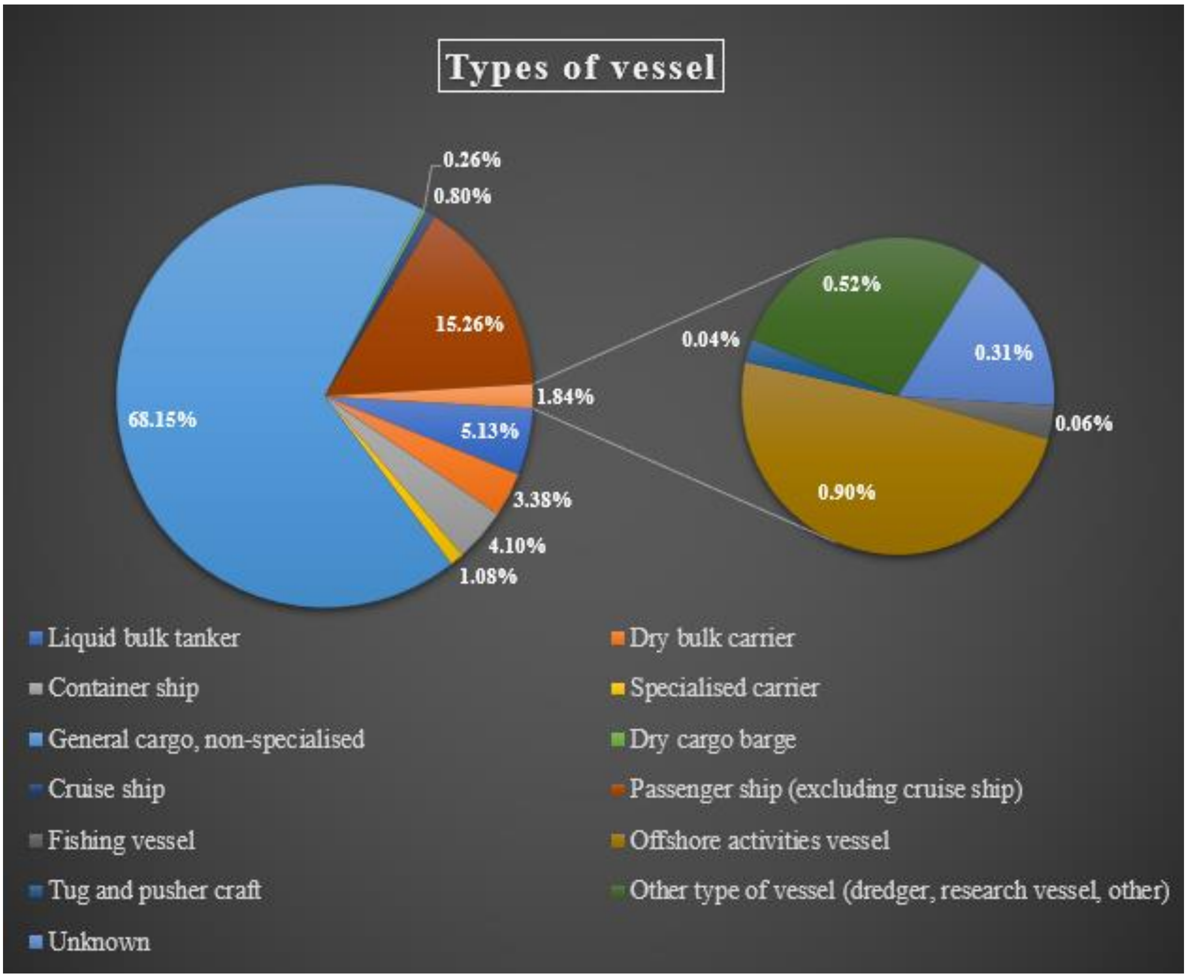


Figure 2.4 Vessel types

The other types of cargo vessels represent 13.95% of the total number of vessels encountered. Spain is an important area for liquid and containerized cargo vessels and ranks third in terms of dry cargo.

2.6 Volume in TEU

Containerized freight transport has developed with globalization [30] and is increasingly popular due to the large quantities of goods that can be transported in a single journey, as well as the diversity of categories of goods that can be transported in this way.

To illustrate the growth trend of containerized freight transport, the number of containers handled per year (Figure 2.5) has been plotted. The highest developments are in Spain, Greece, and Turkey.

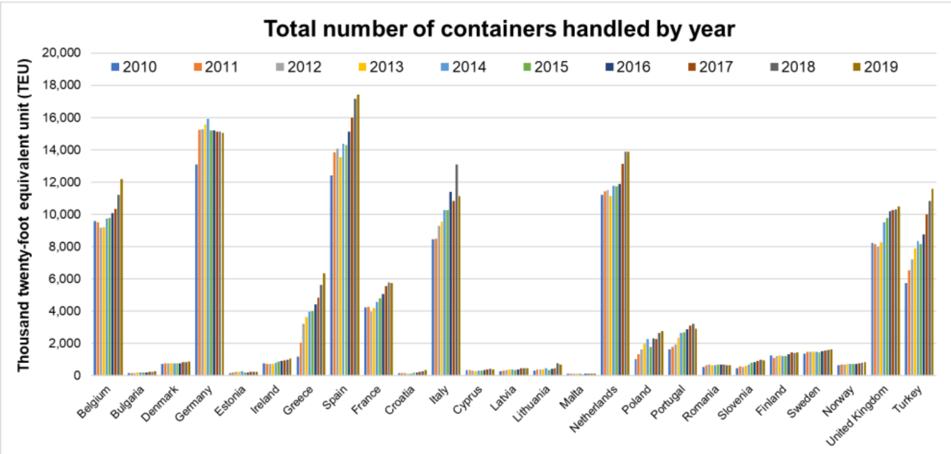


Figure 2.5 Total number of containers handled by year

2.7 Passenger ships

Passenger ships are divided into two main groups: ferry passengers and cruise passengers. Economic growth ([24], [31]) as well as the possibility to travel more easily, increase people's desire to visit as many destinations as possible on vacations, choosing cruise ships as a holiday option.

The density of passengers embarking and disembarking at all ports over the ten years is illustrated in Figure 2.6. Of the total 4 199 289 thousand passengers, the highest number was registered in Italy, Greece, and Denmark. Germany and Sweden rank fourth almost 300,000 thousand passengers.

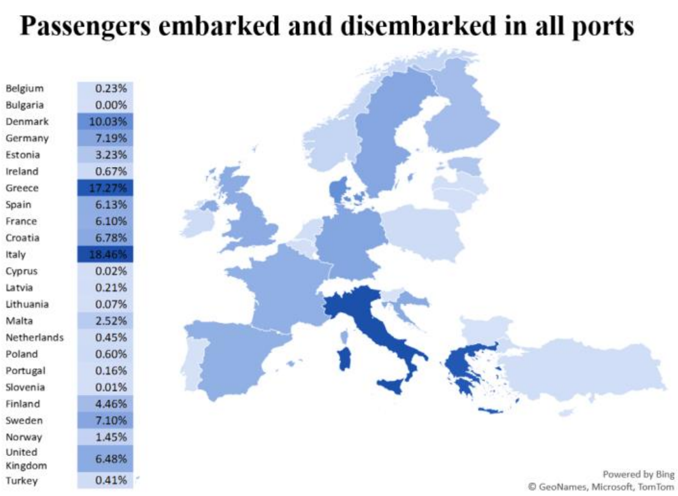


Figure 2.6 Passengers boarded and disembarked.

2.8 Top 20 Ports

Even though the ranking of ports may change from year to year, the top positions remain constant, regardless of economic fluctuations, but with minor changes between positions. Based on the information generated for the period 2010-2019, a list of the top 20 ports in Europe has been compiled, shown in Figure 2.7, according to the total number of thousands of tonnes of cargo registered. In the top 20 ports considered, 16 919 482 cargoes were transited, of which most were in Rotterdam, Antwerp, Hamburg, and Amsterdam.

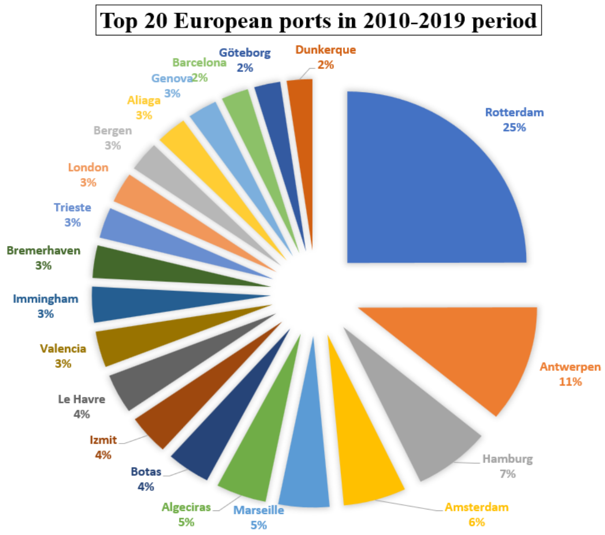


Figure 2.7 Top ports in the 2010-2019 period

2.9 Accidents

Based on data provided by Eurostat [1], an analysis of maritime accidents for the period 2010-2019 was carried out, according to the area where they occurred (Figure 2.8)

Of the total of around 3 400 people involved in accidents, 23% occurred in the Mediterranean Sea and 16% in the Atlantic Ocean, considered the most dangerous sailing areas due to unpredictable weather conditions. In total, 3 047 people were injured and 317 lost their lives in Europe during the period studied.

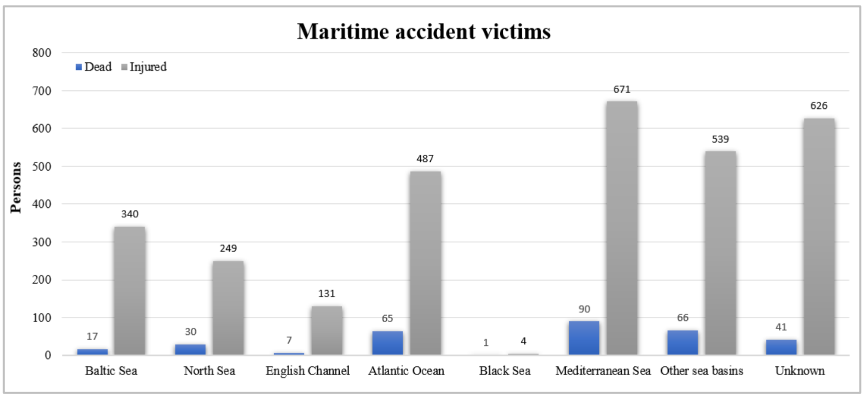


Figure 2.8 Maritime accident victims by zone

2.10 Conclusions

In this chapter a series of statistical analyses have been carried out for the period 2010-2019, based on information extracted from the Eurostat database [1] concerning goods handled in all ports, types of goods, types of vessels, volume in TEUs, and passenger's vessels. On this basis, the top 20 ports for each category were identified. A survey of maritime accidents, both in terms of area and type of ships, that occurred during this period was also carried out.

In all ports in Europe, a large number of thousands of tonnes of cargo was registered during the period under review, and the main countries leading this industry are the Netherlands, the United Kingdom, Turkey, Spain, Italy, and France. The annual distribution of cargo volume is uniform, with each country maintaining its cargo numbers at a slightly different level.

The types of goods that have been studied are liquid bulk goods, dry bulk goods, large containers, other types of goods, and mobile units. Most liquid goods were transited by the Netherlands, and this category was the most popular during the ten-year period. The second most popular category is dry goods, and this market was dominated by Turkey. The container category is taken by Spain, and in the Ro-Ro mobile unit category, the United Kingdom is the leader.

A variety of types of goods transit Europe, in many categories, such as: agricultural products, forest products, food, textiles, metals, coal, oil, natural gas, and more. Most of these are coal, crude oil, and natural gas, and were mainly transited by the Netherlands and the United Kingdom. The next category is coke and refined petroleum products, held by Spain and the Netherlands, and the last category is mineral products, and most of these were transited by Norway.

The types of ships that have safely carried the cargoes are general cargo ships as well as a number of cargo-specific ships. Although general cargo ships dominated the ship types encountered with 68%, passenger ships ranked second with 16%. A further 2% of the total number of ships transiting European waters during the period studied were fishing vessels, research vessels, offshore vessels, and other types of vessels contributing to the management of maritime traffic. The highest number of passengers travelling in Europe was recorded in Italy, Greece, Denmark, Germany, and Sweden. An important contribution to the total number of passengers is influenced by cruise passengers, especially in Italy and Greece.

Handling goods in containers is a method that is becoming increasingly popular due to the safe conditions in which goods are transported, the low price, the diversity of products that can be transported in containers, and the large quantities that can be transported. This type of vessel has undergone a process of optimization to improve its characteristics, reduce fuel consumption and thus reduce pollution. The highest volume of cargo for this category was recorded in Spain, Germany, and the Netherlands.

The leading ports in the period 2010-2019 were Rotterdam (in terms of liquid bulk and dry bulk cargo and large containers and container volumes), Dunkirk (in terms of Ro-Ro mobile units - self-propelled), Immingham (in terms of Ro-Ro mobile units - un-propelled) and Dover (in terms of passengers embarked and disembarked).

Shipping accidents can cause losses in terms of cargo, human lives, and even the entire flow of trade due to delays. The Mediterranean is one of the most accident-prone areas in Europe, but fortunately in most incidents during the reporting period, only 10% of the total number of people injured died. Fishing vessels, cargo ships, and passenger ships were the main categories involved in such events.

Rising maritime traffic density has put pressure on the transport industry, especially on port areas, which need to be upgraded in terms of space to handle goods more easily, equipment that needs to be related to the development of technology, and training of personnel involved in these operations.

The research presented in this chapter is an extended and updated version of the originally published articles:

1. **Chiroşcă Ana-Maria**, Liliana Rusu, 2021. Statistical analysis of the types of ships, maritime accidents and casualties in European Waters for the last decade, submitted at SWS Journal of Earth & Planetary Sciences (EPS), accepted for publication
2. **Chiroşcă Ana-Maria**, Rusu Liliana, 2020. Statistical analysis of the types of ships that have crossed the European ports in the last decade. 20th SGEM International Scientific Conferences on Earth & Planetary Sciences, Extended Scientific Sessions „GREEN SCIENCE FOR GREEN LIFE" SGEM Vienna GREEN 8-11 December 2020, Vol. 20, 249-256, ISBN 978-619-7603-17-0. https://doi.org/10.5593/sgem2020V/1.3/s02.31 (indexed Scopus)

CHAPTER 3 – WIND AND WAVE CLIMATE CHARACTERISTICS THROUGHOUT THE EUROPEAN SEAS

3.1 Introduction

Shipping is directly affected by weather conditions, often in a negative way. For this reason, a study of wind and wave parameters is necessary to ensure smooth transport, to prepare the ships' crews, and to avoid unfortunate events as often as possible.

The investigation of climate change's effects on wind and wave conditions is a current trend both in terms of simulations for the past ([32] to [34]), to identify the pattern of these parameters but also for the near future ([35] to [40]). Every sea in Europe has its special features. The Caspian Sea has the characteristics of a sea, but also of a lake. Due to weather conditions and strong winds, sea levels can rise to three times higher. Tides and seasonal changes do not affect the intensity of these parameters.

Climatic conditions also have a major impact on inland navigation in Europe, especially on the Danube-Black Sea Channel ([15], [16])and Rhine-Main-Danube Channel [20] due to several factors. Although they have been designed to be as easy and safe to navigate as possible, and are safer than maritime navigation, due to climatic conditions there can be problems with water depth, some bends and crossings become dangerous to cross, and the tide or counter currents can affect the maneuverability of vessels.

Based on the maritime traffic density presented in Chapters 1 and 2, as well as interactive ship observation maps based on information provided by the "World Meteorological Organization" (WMO) [41], and global shipping route data from the ArcGIS platform [42], the most popular routes in Europe were identified and shown in Figure 3.1. Details of these routes are shown in Table 3.1.

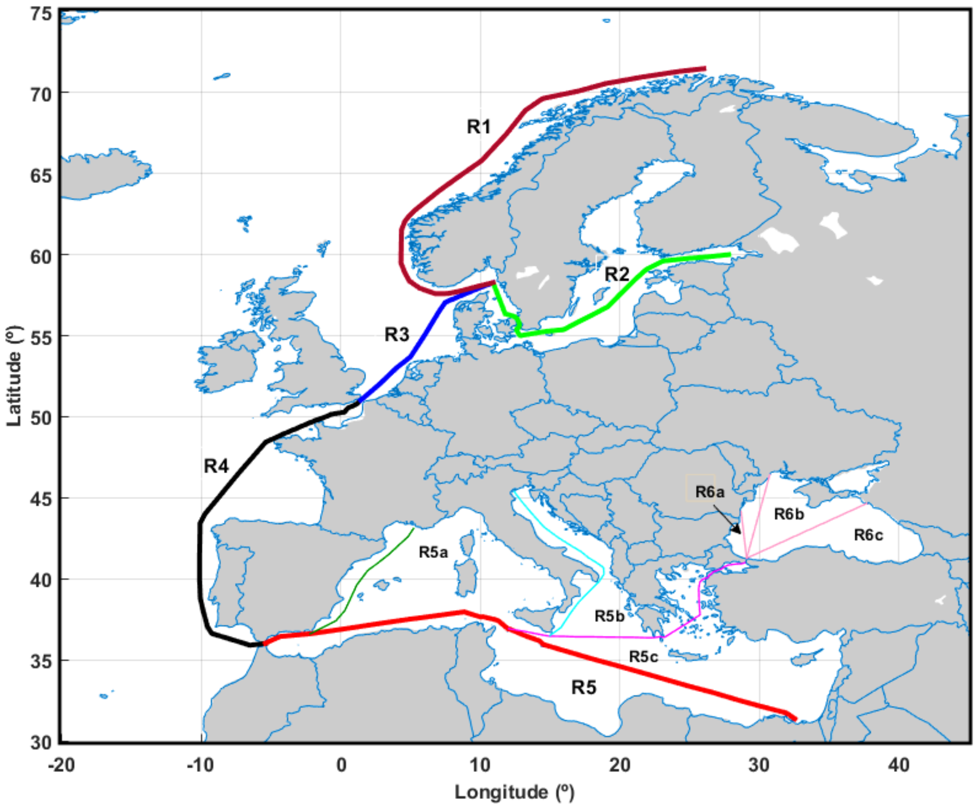


Figure 3.1 Main European routes [32]

Table 3.1 European routes [32]

Routes		Length (nmi)	Seas crossed
Main routes	R1	1280	Norwegian Sea
	R2	814	Baltic Sea
	R3	585	North Sea; Northern English Channel
	R4	1266	English Cannel; Bay of Biscay; North Atlantic Ocean
	R5	1911	Mediterranean Sea
Secondary routes	R5a	487	Western Mediterranean Sea; Gulf of Lion
	R5b	710	Ionian Sea; Adriatic Sea
	R5c	985	Sicilian Channel; Ionian Sea; Sea of Crete; Aegean Sea; Marmara Sea
	R6a	178	Western Black Sea
	R6b	323	Western Black Sea
	R6c	495	Black Sea

Six main routes were identified, and two of these were divided into three secondary routes; In Figure 3.1, the main routes are shown with thicker lines, and the secondary routes with thinner lines.

3.2 Data used in climate analysis

For this study, the latest data from European Centre for Medium-Range Weather Forecasts (ECMWF) was used. ECMWF [43] oversees producing weather forecasts, maintaining a data archive, and improving forecasting capabilities. It manages the “Copernicus Atmospheric Monitoring Service (CAMS)” and the “Copernicus Climate Change Service (C3S)”.

In this chapter, the data used for wind and wave climate for the period 2001-2020 have been extracted from the 5th generation ERA5 [44] database provided by the Copernicus Climate Change Service (C3S). These represent the new generation of reanalysis database for global climate and weather, with improved resolution compared to the previous generation, ERA-Interim [45], as well as better consistency of sea surface temperature and sea ice, better representation of tropical cyclones, and more.

From the six established sea routes, six areas were chosen for the study of climatic conditions, shown in Table 3.2. Boundaries have been highlighted for three of the areas whose basins are not clearly defined on the map (the Norwegian Sea, the North Sea, and the area consisting of the English Channel and the Celtic Sea). The other three areas are large semi-enclosed areas, namely the Black Sea, the Mediterranean Sea, and the Baltic Sea.

Table 3.2 The geographical zones investigated [32]

Zone	Coordinates	Surface area [km^2]	Average depth [m]	Maximum depth [m]
Black Sea	27°E – 42°E / 41°N – 47°N	436,402	1253	2212
Mediterranean Sea	5°W – 35°E / 30°N – 40°N	2,500,000	1500	5267
English Channel	15°W – 10°E / 45°N – 51° N,	375,000	63	174
North Sea	5°W – 10°E / 51°N – 60°N,	570,000	95	700
Baltic Sea	12°E – 32°E / 53°N – 65°N,	377,000	55	459
Norwegian Sea	10°W – 25°E / 60.5°N – 74°N	1,380,000	200	3970

For two of the seas studied, an estimate of the future projection of the sea state conditions has also been made. In the Black Sea, this analysis was carried out to observe the influence of climate changes through a comparison between wind and wave climate conditions between 2001-2020 and the near future.

As the exploitation of wind energy is one of the current trends and wind farm development is a priority in Europe [46], the North Sea and the Mediterranean Sea were analyzed from this perspective. In the case of the North Sea, a study on wind farms and their status, as well as the classification societies' approach to them, was carried out, while the Mediterranean Sea was studied using wind data simulated in the RCP4.5 (Representative Concentration Pathway) scenario by a regional climate model, as in the case of the Black Sea.

The dataset used for the near-future projection is provided by SMHI ("Swedish Meteorological and Hydrological Institute") in the EURO-CORDEX ("European Domain-Coordinated Regional Climate Downscaling Experiment") experiment [47] and was simulated under the RCP45 scenario [48].

3.3 Analysis of wind climate

Wind speed for the period 2001-2020 was calculated using the eastward component (u [m/s]) and the northward component (v [m/s]) of the wind at 10 m height above sea level provided by the ERA5 database [43].

To begin with, an analysis of average wind speed values in areas of Europe was carried out, as can be seen in Figure 3.2, where the maximum position has been marked with a black circle. In the period 2001-2020, the maximum mean value is found towards the Atlantic Ocean and has a value of 9.8 m/s. Among all European seas, the highest mean values were recorded in the North Sea, the English Channel, and the Norwegian Sea. Due to the wind values as well as the shallow waters, the North Sea wind platform industry [49] is well established and is the most developed sea in Europe in this field. Another sea where we also find high values of average speeds is the Norwegian Sea and, according to other studies ([50], [51]), these values will continue to be maintained.

Another sea with offshore wind potential, although the average values encountered are lower, is the Black Sea ([52] to [55]). The Mediterranean Sea has similar values to the Black Sea, but there are also areas such as the Gulf of Lion and the Aegean Sea ([56], [57]), where the average values are higher, reaching 8.5 m/s.

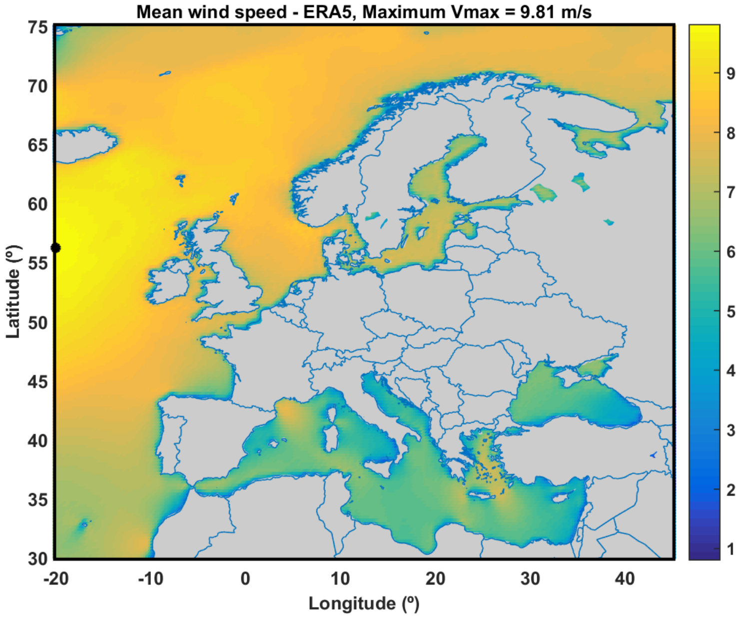


Figure 3.2 Mean wind speed, 2001-2020 [32]

In order to observe how the mean wind speed varies by season, an analysis was carried out where the months were divided as follows: MAM (spring), JJA (summer), SON (autumn) and DJF (winter).

A statistical analysis of wind speed for the period 2001-2020 in Europe was also carried out using a Matlab algorithm in which the following percentiles were calculated: 50 (indicates the median of the distribution and is known as the second quartile Q2), 75 (the third quartile, Q3), 90 (indicates the value below which 90% of the data is found and above which only 10% is found) and 95 (indicates the value below which 95% of the data is found and above which only 5% is found). These are shown in Figure 3.3 and help to be able to analyse the data in percentages and give a picture of the extreme values found in Europe.

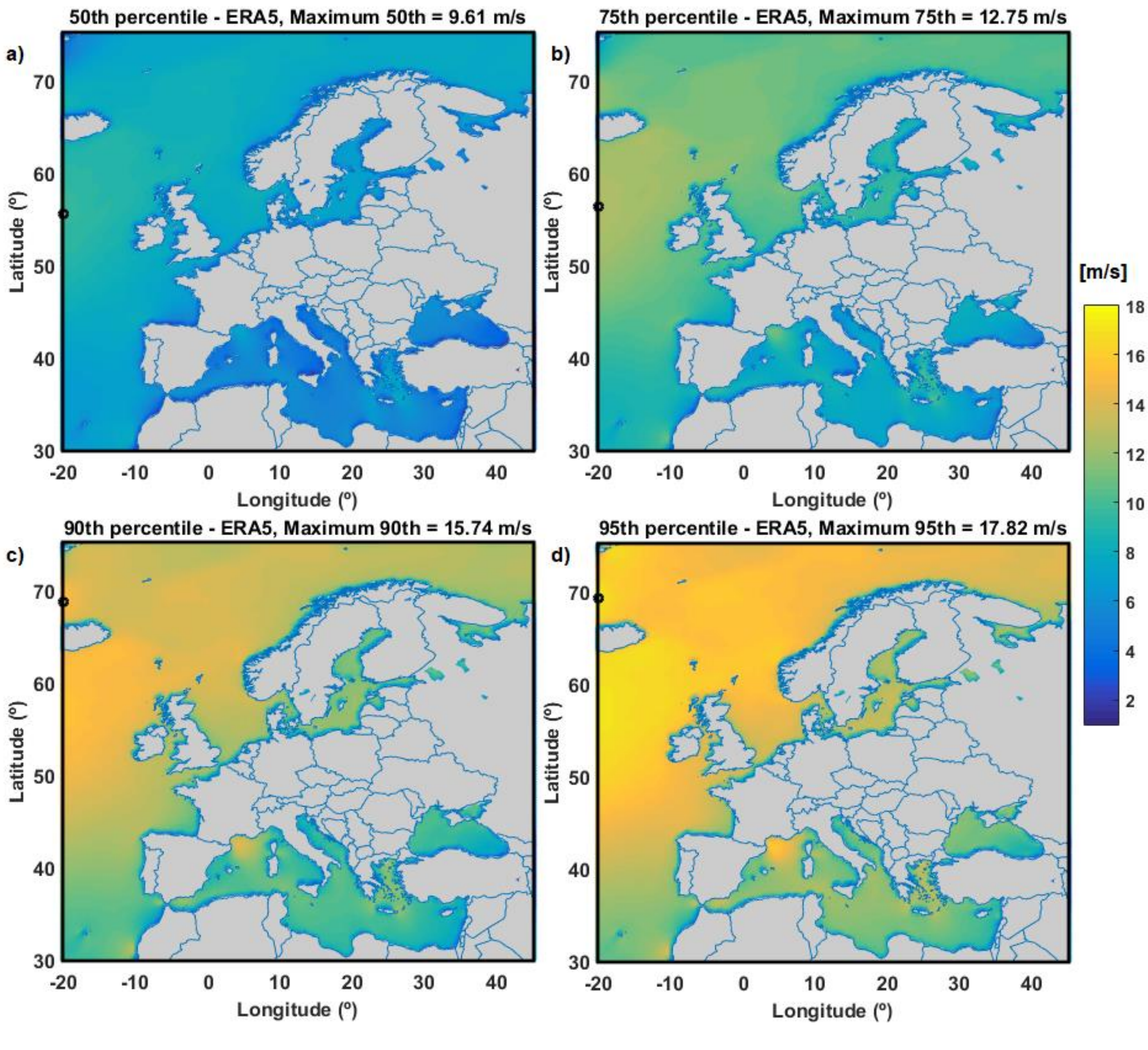


Figure 3.3 Statistical investigation on wind speed: (a) 50th percentile; (b) 75th percentile; (c) 90th percentile; (d) 95th percentile [32]

The 95th percentile was also plotted for the main routes in the major European area (Figure 3.4 and Table 3.3). The highest values were found along the Norwegian and the Western Mediterranean route, specifically in the Gulf of Lion, where values above 15 m/s were found. Values of 14.5 m/s were also found along the route defined in the North Sea as well as along the route across the English Channel and the North Atlantic Ocean. The lowest values were found along the main Black Sea routes.

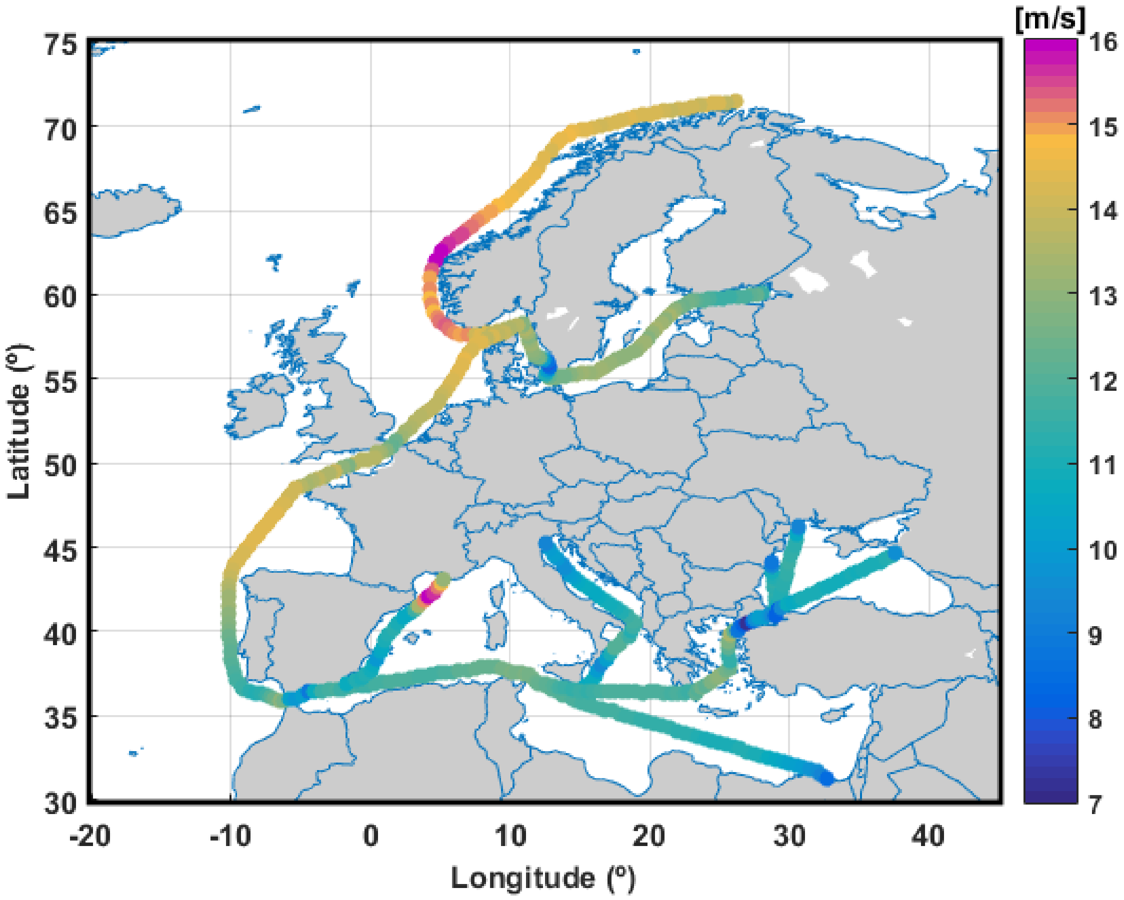


Figure 3.4 95th percentile of wind speed along the European marine routes [32]

Table 3.3 Maximum wind speed considering 95th percentile [32]

Routes		Maximum wind speed 95th percentile (m/s)
Main routes	R1	15.98
	R2	13.59
	R3	14.51
	R4	14.43
	R5	12.75
Secondary routes	R5a	15.92
	R5b	11.93
	R5c	13.34
	R6a	11.39
	R6b	11.60
	R6c	11.32

3.4 Analysis of wave climate

The wave climate was investigated based on two important parameters, wave height and wave period, which directly influence the sea state and the way ships operate. Thus, average values for these two parameters were generated for all areas considered.

From the seasonal characteristics of 95th percentiles it can be seen that the mean maximum values of wave heights in winter are double those in summer. Mean values during spring and autumn are more balanced, with predominantly high values in September, October, and November. A difference can be seen in the case of the North Sea, where the difference from summer to winter is significantly greater.

The English Channel is described as the area with the most critical wave climate conditions in winter when values of 3.15 meters for the maximum mean wave height and 6.74 seconds for the maximum mean wave period are recorded.

The Black Sea is the calmest area in Europe, with the lowest maximum mean values, 0.72 meters for wave height and 3.28 seconds for wave period.

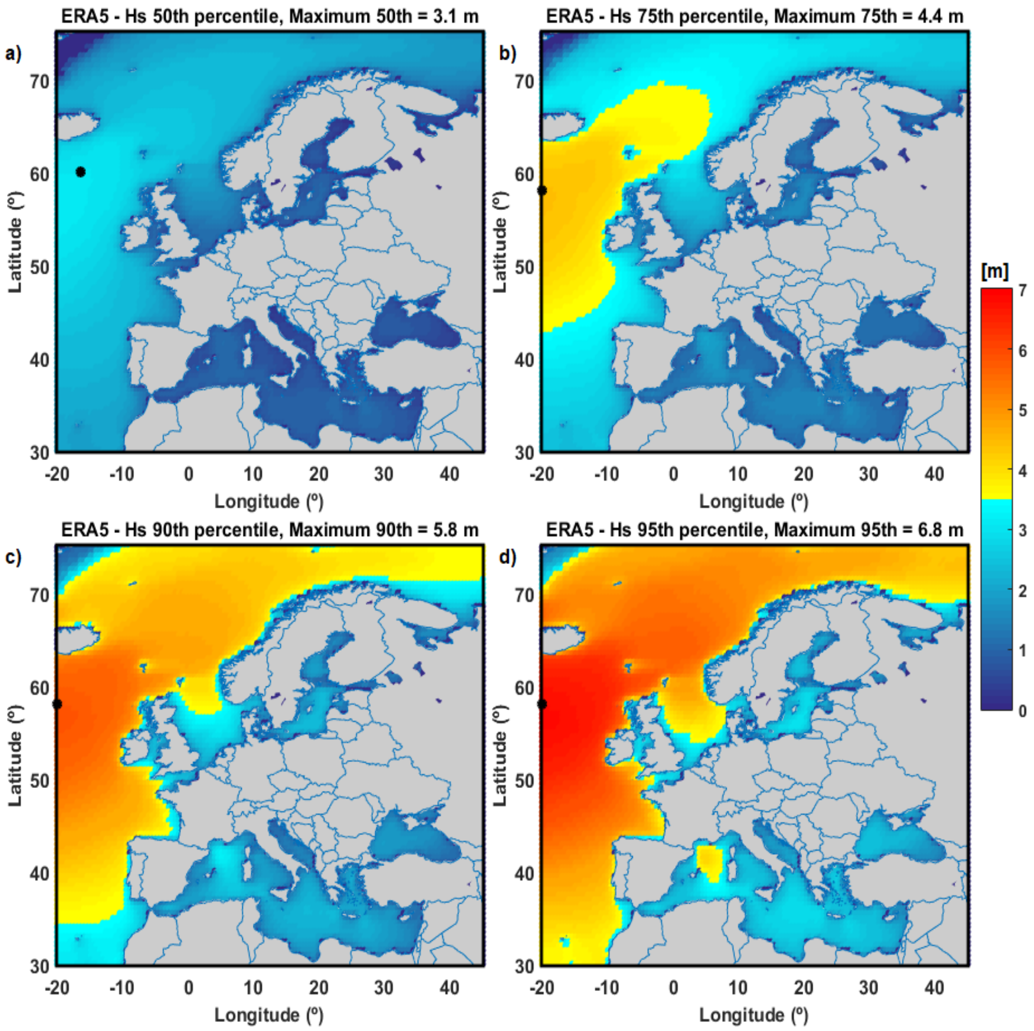


Figure 3.5 Wave height circumstances statistically investigated: (a) 50th percentile; (b) 75th percentile; (c) 90th percentile; (d) 95th percentile[32]

3.5 North Sea - Wind farm investigation

3.5.1 Climate analysis

The climate in this area is temperate, with all-season rainfall throughout the year and tides of up to 6 meters in the southern coastal area, while in the north and east, they are significantly lower. Analysis of the North Sea climate was carried out using ERA5 data [43], as detailed at the beginning of this chapter and shown in Figure 3.6. The mean maximum values encountered are higher than in other regions of Europe, and for the period studied the mean maximum wind speed is 9.52 m/s, wave height is about 3.4 m, and wave period is 6.85 s.

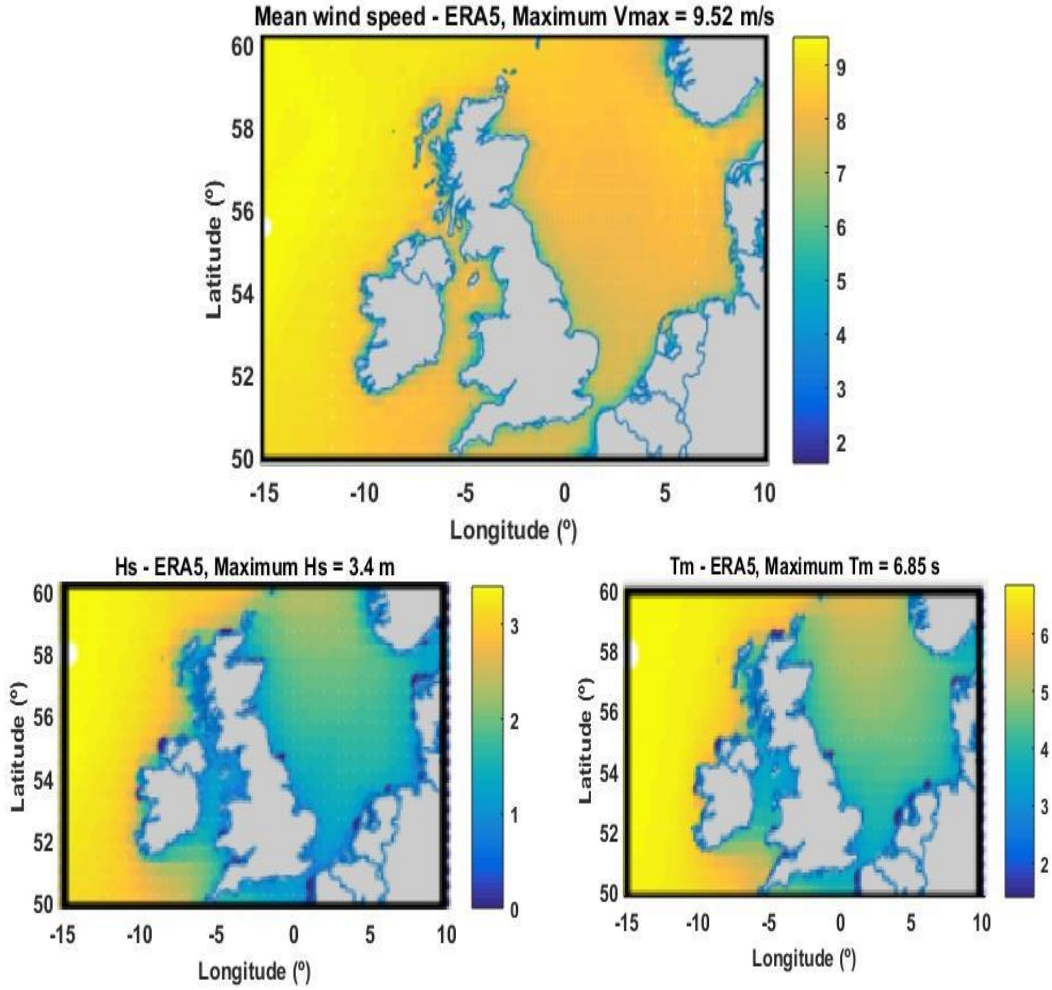


Figure 3.6 Analysis of the North Sea regarding wind climate and wave climate for the 2001-2020 period [58]

3.5.2 Wind farms

According to the Global Offshore Wind Farm Map and Database [59], more than 41 wind farms are installed in the North Sea area, with about 2 600 turbines and a capacity of more than 100 000 MW. It can be seen that the offshore field is expanding rapidly, where wind farms are shown according to their status (Figura 3.7): early planning, application submitted, consent authorized, pre-construction, under constructions, fully commissioned, decommissioned and development zone.

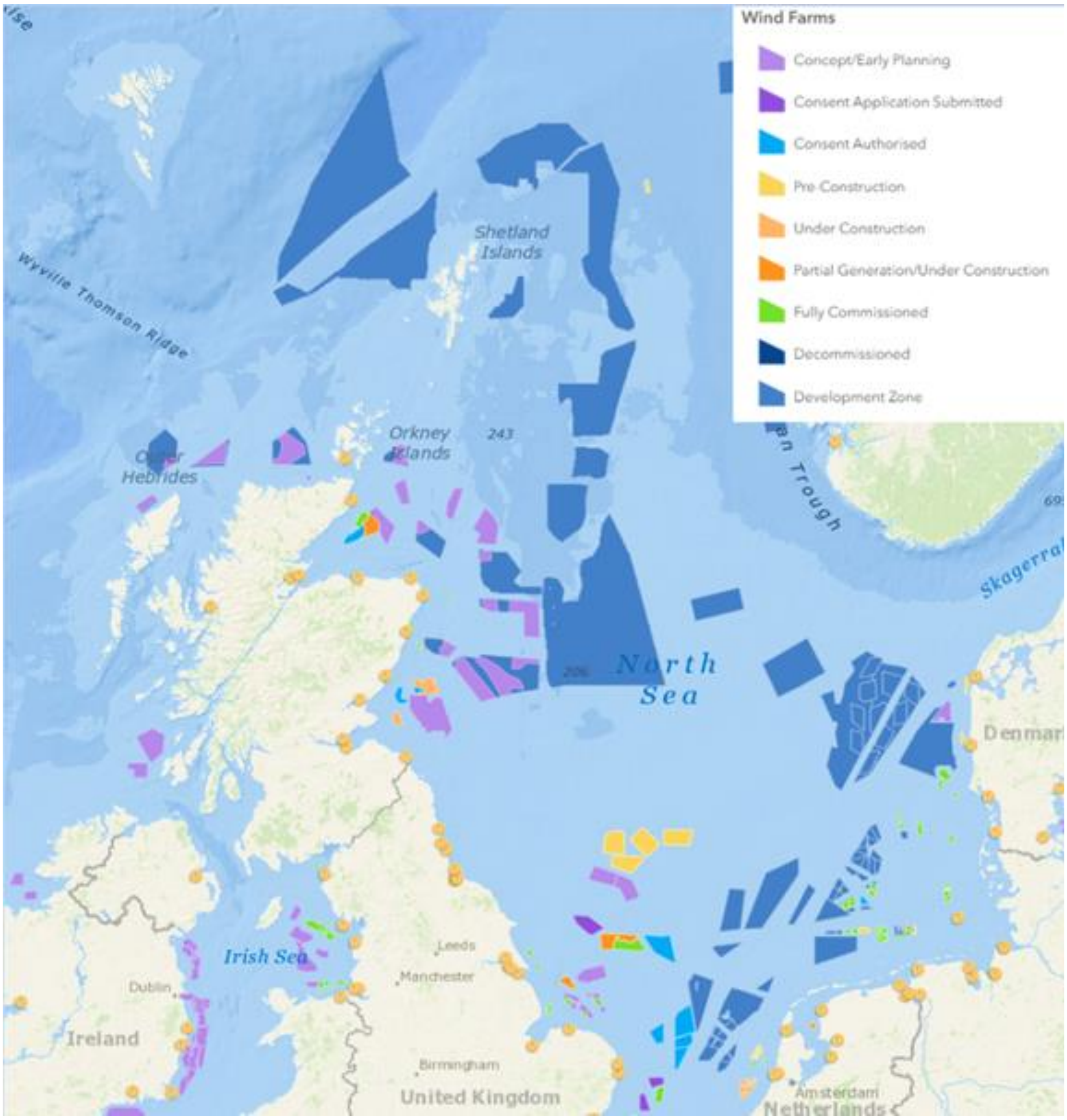


Figure 3.7 Wind farms

Based on the wind farms identified, a classification according to the type of turbines has been made. It demonstrates that more over half of all installed turbines in this sea are Siemens models, making them the most often used. Vestas turbines, which make over 25% of all turbines, are next in line.

3.6 Mediterranean Sea – Wind farm investigation

3.6.1 Wind farms

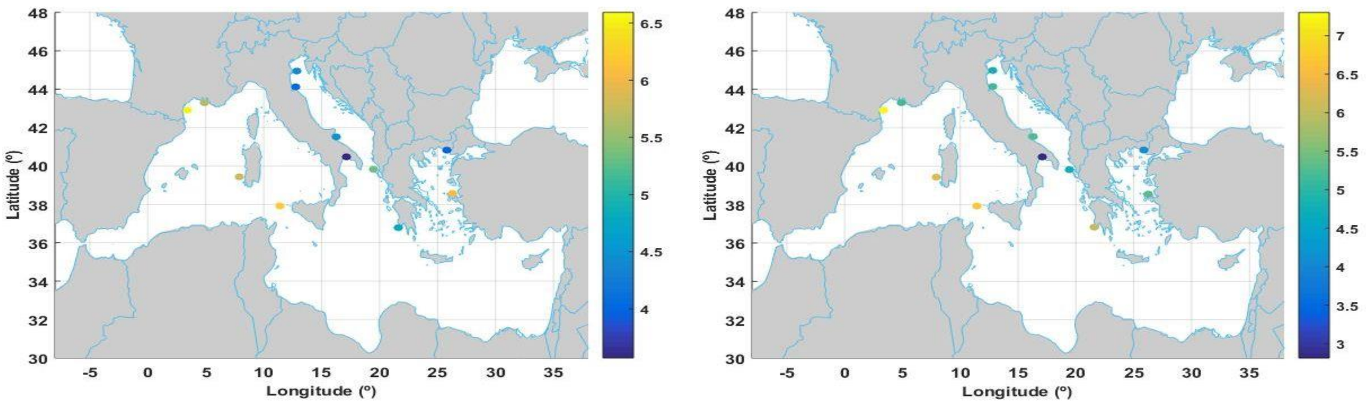
Based on EMODnet data [60], 36 wind farms have been identified, which are represented in Figure 3.8 according to their status: approved, decommissioned, planned, in production, under construction, and in the testing stage. Of these, only four are under construction, and when completed the 36 wind farms will produce about 8 000 MW [61].

Figure 3.8 Wind farms positions [61]

3.6.2 Wind climate

The climate in the reference area is a temperate Mediterranean climate, where the summer months are hot but dry and the winters are wet and mild [62]. Because of the complexity of the Mediterranean Sea basin, a study of the wind climate is necessary, although some climate studies claim that the variability of this parameter will not exceed 15% [63] for Europe in the coming years.

Figure 3.9 shows the average seasonal values investigated for the period 2001-2020, using ERA5 data [43], compared to the values for the period 2017-200 under the RCP4.5 scenario [48].



2001-2020 – ERA5 2071–2100 RCP4.5

Figure 3.9 Mean wind speed [61]

3.7 Black Sea – Comparison of wind and wave climate regarding past and near future projections

3.7.1 Wind climate

The wind climate was studied along the three Black Sea routes presented in subchapter 3.1. As in the Mediterranean study, ERA5 data for the past and RCP4.5 scenario for the near future, were used. Comparative maps for the period 2001-2020 and the period 2021-2050 for each season are shown in Figure 3.10.

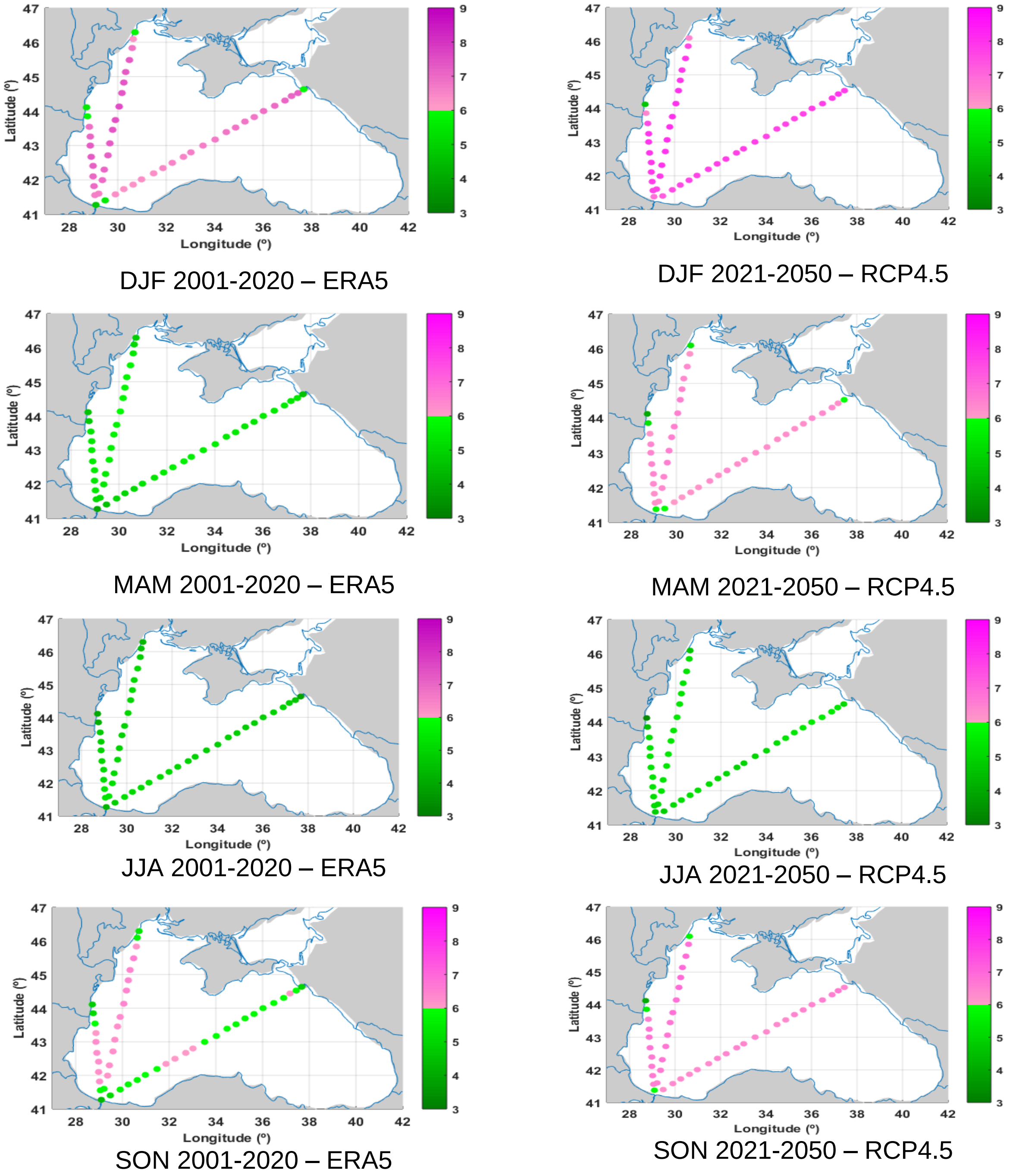


Figure 3.10 Seasonal variability of the mean wind speed [64]

3.7.2 Wave climate

Similar as for the case of the wind climate study, a wave climate study was carried out considering the same routes. The comparison of mean wave height values between past and near future data is shown in Figure 3.11. A statistical analysis of the extreme values encountered in this area was also performed.

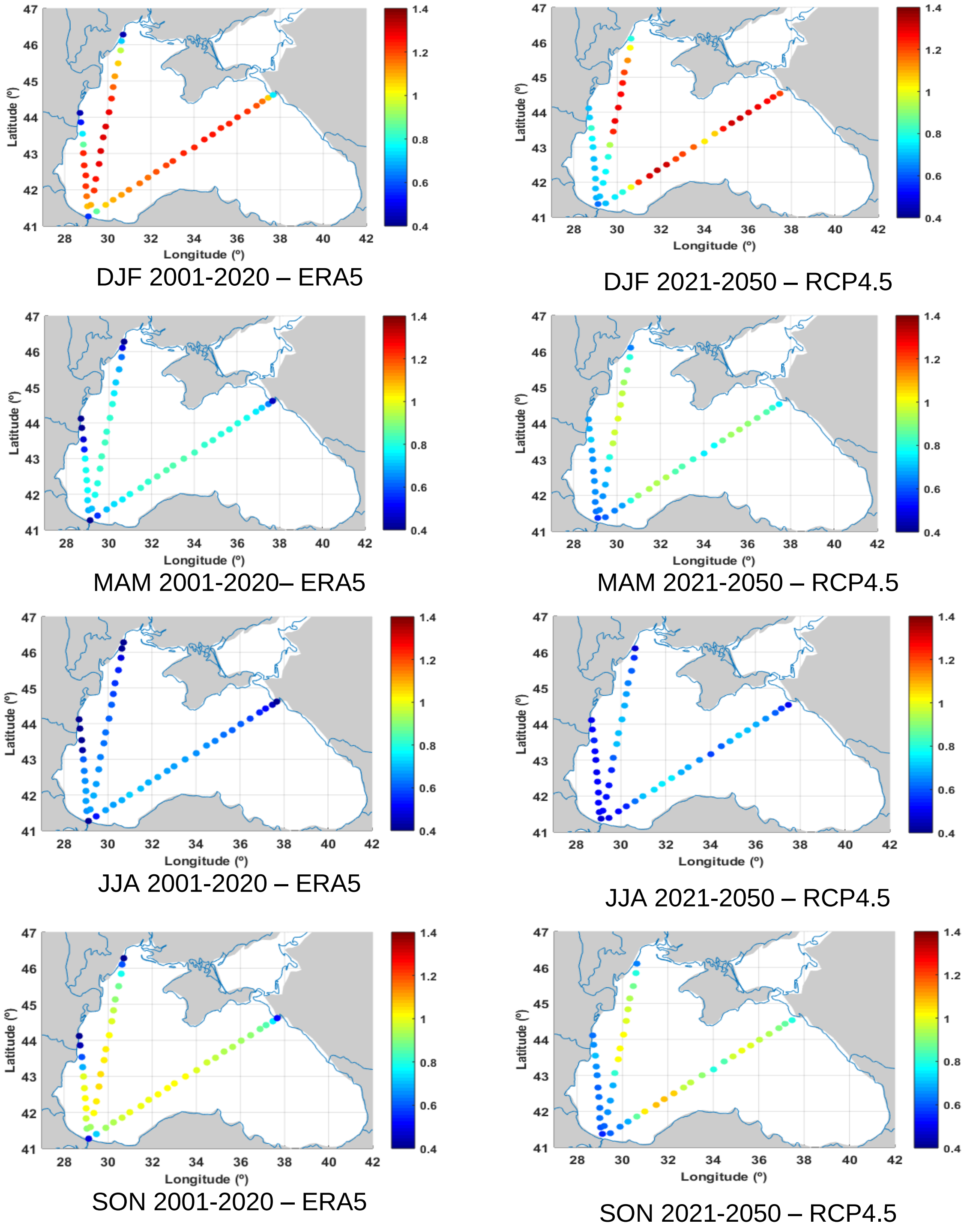


Figure 3.11 Seasonal variability of the mean wave heights [64]

3.8 Conclusions

Climate change is directly affecting European weather conditions, with rising sea temperatures, stronger winds, higher waves, and many other effects. An analysis is therefore needed to identify current conditions, past conditions, and how they will develop in the future. Extreme conditions also need to be identified to ensure that they will not affect shipping.

In this chapter, wind and wave climate characteristics for European seas have been presented. The data used for this study and the areas considered were specified. Next, the results of the study on wind climate, wave climate study, and extreme values encountered were presented. This chapter also includes a wind farm study for the North Sea and the Mediterranean Sea, as well as a transport study in the Black Sea considering wind and wave climate.

The analysis was carried out for a 20-year period starting in 2001 and, based on ERA5 data, mean values, 50th, 75th, 90th and 95th percentiles, seasonal variations, and maximum conditions were identified. This analysis was applied to both the European seas and the most important shipping routes in the area. The parameters studied were wind speed, significant wave height, and wave period.

In the North Sea and the English Channel region, the highest mean values have been identified for both wind and wave climate. The Black Sea and the Baltic Sea are the calmest seas, but the winter months can be problematic for shipping ([65] to [68]). Concerning the sea routes studied, the highest values are found on the route to the Norwegian Sea and in the Bay of Lyon. Seasonal variations in Europe are about 40%.

The Black Sea is important for shipping because of its connectivity with the Danube, but also for international trade through the Turkish Straits. The wind and wave climate for the next two decades is expected to worsen, and to combat these effects, the shipping industry needs to adapt and improve.

Green energy or renewable energy is a topic of current interest due to the desire to combat the effects of climate change, as well as to replace fossil fuels, which not only pollute, but cost a lot and the cost continues to grow with the outbreak of war between Russia and Ukraine.

The generation of green energy especially in the port area has several benefits, besides contributing to the production of electricity for the local area and for the docked ships, helping to combat pollution generated by them while they are stationed. As such, the potential of wind farms in Europe's busiest shipping seas, the North Sea and the Mediterranean, has been investigated. The climate of the North Sea encourages the development of renewable energy industries, especially when it comes to offshore wind platforms. This area is home to the most wind farms in Europe. Although there are currently no operational wind farms in the Mediterranean Sea, in the coming years the area is set to see a significant increase in offshore wind energy.

It is therefore important to know the wind and wave climate trends in Europe so that dangerous areas can be avoided, and shipping accidents reduced. For the offshore industry, knowing and studying the climate helps to identify the best areas for exploitation, better operation, and installation.

The research presented in this chapter is an extended and updated version of the originally published articles:

1. **Chiroşcă Ana-Maria**, Rusu Liliana, Bleoju Anca, 2022. Study on wind farms in the North Sea area, Energy Reports, Volume 8, Supplement 16, Pages 162-168, ISSN 2352-4847,https://doi.org/10.1016/j.egyr.2022.10.244, Impact factor 4,937
2. **Chiroșcă Ana-Maria**, Rusu Liliana, 2022. Characteristics of the wind and wave climate along the European seas focusing on the main maritime routes, Journal of Marine Science and Engineering, 10(1), 75. https://doi.org/10.3390/jmse10010075 Impact factor 2,574, Q1
3. **Chiroşcă Ana-Maria**, Rusu Liliana, 2022. Study of climate changes and their impact on maritime transport in the Black Sea area, Proceedings of 22nd International Multidisciplinary Scientific GeoConference SGEM 2022, Volume 22, Issue 3.1. https://doi.org/10.5593/sgem2022/3.1/s12.22
4. **Chiroşcă Ana-Maria**, Rusu Liliana, 2023. Study on Wind Farms in the Mediterranean Sea accepted for ICACER 2023 conference proccedings by Springer Book Series-Green Energy and Technology.

CHAPTER 4 – CASE STUDY ON A TYPICAL CONTAINER SHIP

4.1 Introduction

As the economy grows, so does the need and demand for goods and services. Shipping is the most popular form of transport because of its many advantages. One of the key elements of maritime transport is the transport vessels, which have to go through a process of improvement in order to meet market demand, but also to be able to transport larger loads safely and in a shorter time and to reduce the pollution they cause.

In the European basin, shipping has proven more difficult in recent years as a result of climate change and for this reason, transport ships also need to be linked to the effects this could have on their operability. Container ships have gained popularity in recent years because they can carry various types of cargo in large quantities.

This chapter presents the results of a study carried out on a container ship. The resistance in calm water for a range of speeds was calculated, as well as the response in regular waves.

4.2 Case Study Ship

The investigated hull is a known reference ship for which the results of the simulation in the towing tank are publicly available. It is the “Duisburg Test Case” ship, known as DTC, and represents the hull of a container ship developed at ISMT [69] and designed by the University of Duisburg-Essen.

In this thesis, the naked hull without appendages, which can be viewed in Figure 4.1, was considered for the calculations and the main characteristics are shown in Table 4.1

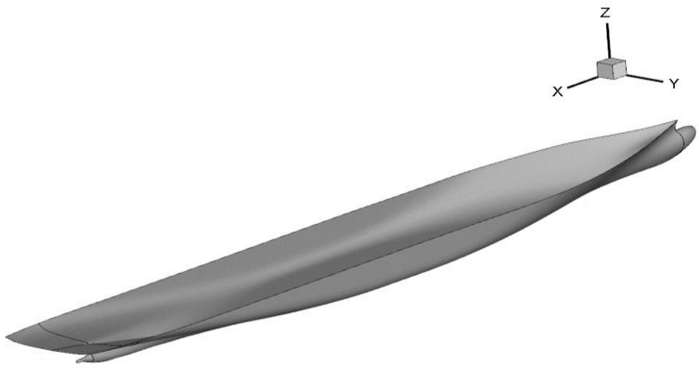


Figure 4.1 DTC hull

Table 4.1 Main Particulars

Main particulars	Unit	Full scale	Model
Length between perpendiculars, L_{pp}	[m]	355	5.976
Waterline breadth, B_{WL}	[m]	51	0.859
Draught midship, T_m	[m]	14.5	0.244
Trim angle, Ʋ	[°]	0	0
Volume displacement, V	[m^3]	173467	0.827
Block coefficient, c_B	[-]	0.661	0.661
Wetted surface, S_w	[m^2]	22032	6.243
Design speed, v	[m/s]	12.86	1.668

4.3 Numerical Approach

Numerical simulations were performed in SHIPFLOW, but in the case of resistance in calm water, ANSYS Fluent and Fine Marine (NUMECA) were also used to compare the results.

The same conditions were imposed in all three programs. The domain was defined around the DTC body according to the model length (1.5 length on the side of the hull, 1.5 length in the front of the hull, 3 lengths behind the hull, 1.5 length below the hull and one length above the hull), and the discretization grid is shown in Figure 4.2.

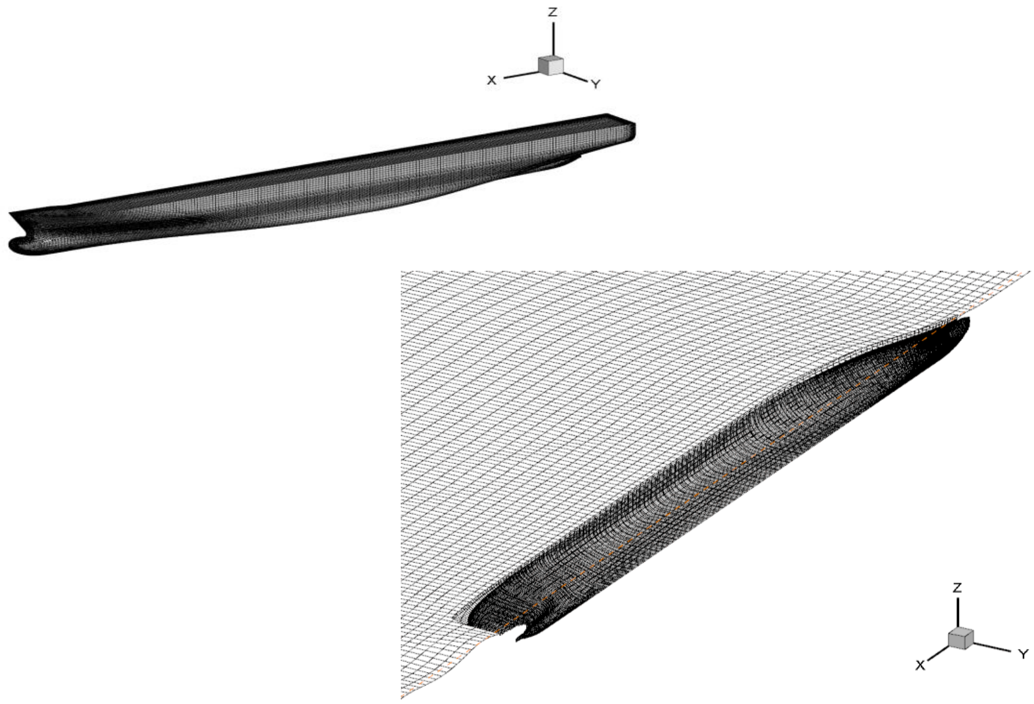


Figure 4.2 Grid of DTC hull

The test cases for each investigated problem will be presented in the subchapter related to each study: resistance, regular waves, and irregular waves.

4.4 Resistance in calm water

The resistance in calm water is an important input for studying the performance of the vessel and for determining the necessary power to be installed on board. With the help of the resistance in calm water, additional wave resistance can be determined, but this will be discussed in the next subchapter.

In this sub-chapter, numerical simulations have been performed in three CFD programs to determine the resistance in calm water. The results have been compared with the results of experimental simulations, performed in the publicly available SVA Potsdam towing tank [69]. The range of speeds used included several six speeds, from 1.335 m/s to 1.668 m/s.

The turbulence model used for the simulations was k-ω SST, but to observe the contribution that the chosen turbulence model has on the solutions obtained, two other turbulence models, k-ω BSL and the EASM model were also carried out in SHIPFLOW.

Figure 4.3 shows the results obtained from the simulations and the comparison with the experimental results. The values obtained in SHIPFLOW using the other turbulence models studied were also plotted.

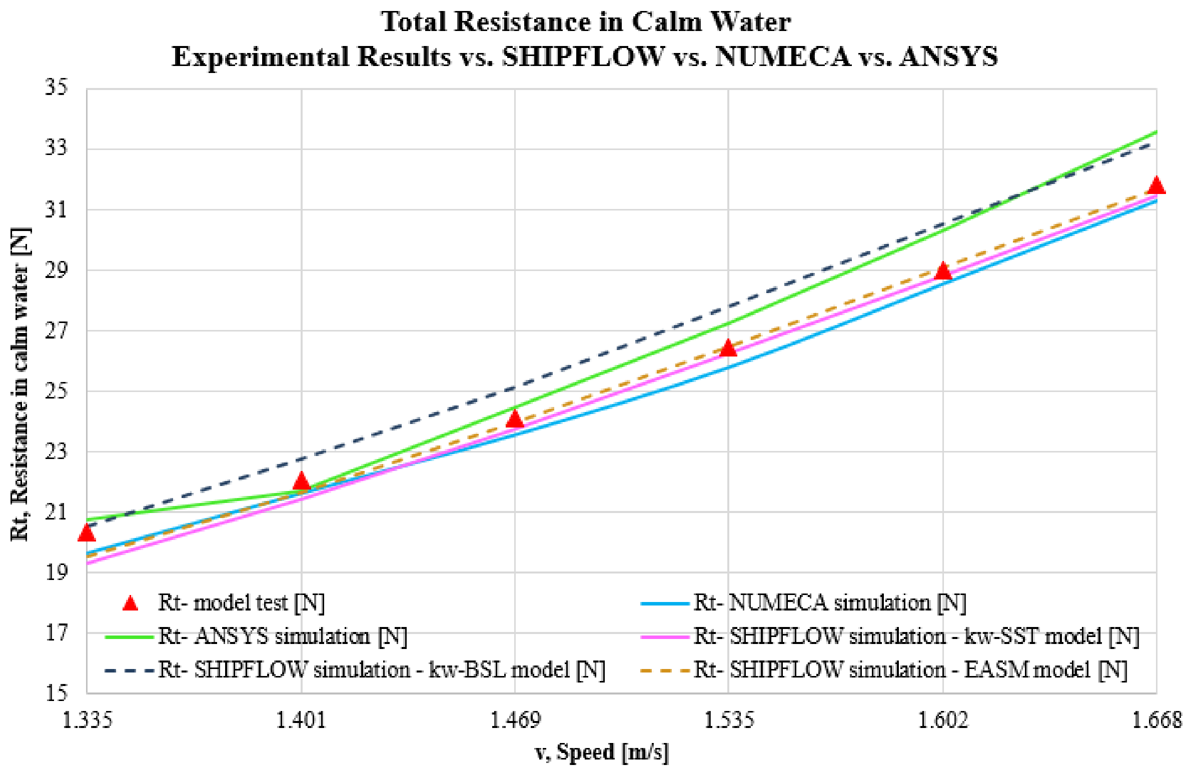


Figure 4.3 Total resistance in calm water

Further, the results obtained in SHIPFLOW were processed and plotted, and the maps for the wave height is shown in Figure 4.4, for the lowest and the highest speed.

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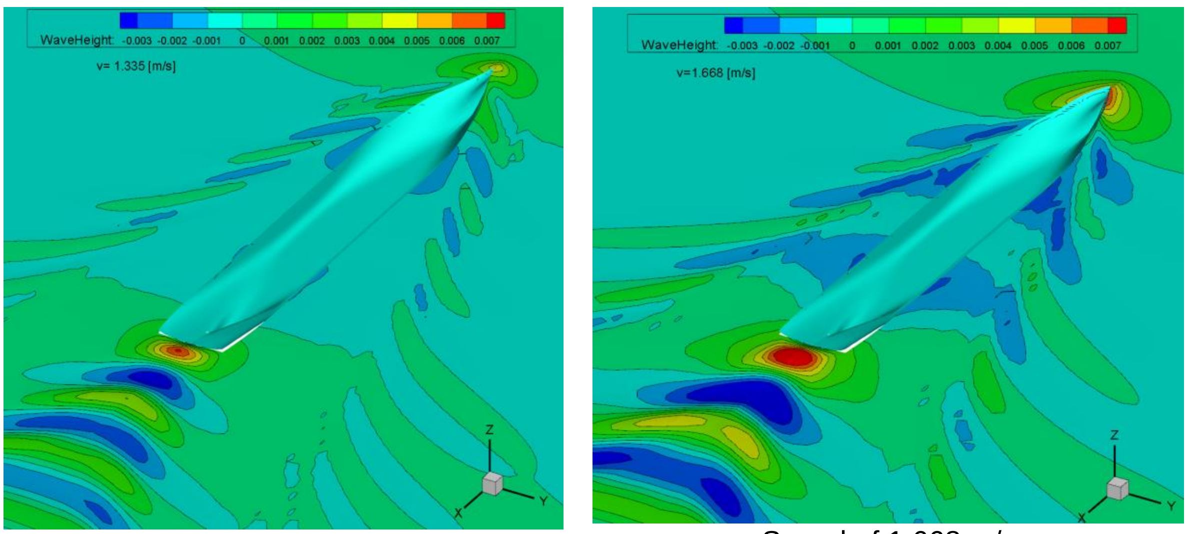


Speed of 1.335 m/s Speed of 1.668 m/s

Figure 4.4 Wave height

4.5 Regular waves

In waves, ships develop much greater resistance, so predicting ship performance in waves is an important element in the preliminary design stage of a hull.

In this subchapter, an analysis of the ship's DTC for a range of wave heights and lengths is presented, and the range of speeds has been adopted for the determination of resistance in calm water so that the additional wave resistance coefficient can be calculated. The test cases are shown in Table 4.2. A convergence test was carried out for several grids to identify whether grid fineness could affect the solutions obtained.

Table 4.2 Test cases for regular waves [70]

Speed v [m/s]	Method	Adimensional wave length λ/Lpp	Adimensional wave height H/Lpp
1.335 1.401 1.469 1.535 1.602 1.668	BEM	0.500 0.750 1.000 1.250 1.500	0.0056 0.0133 0.0169 0.0225

In Figure 4.5 it can be seen what influence the wave length has on the additional wave resistance component and its coefficient when the wave height is constant.

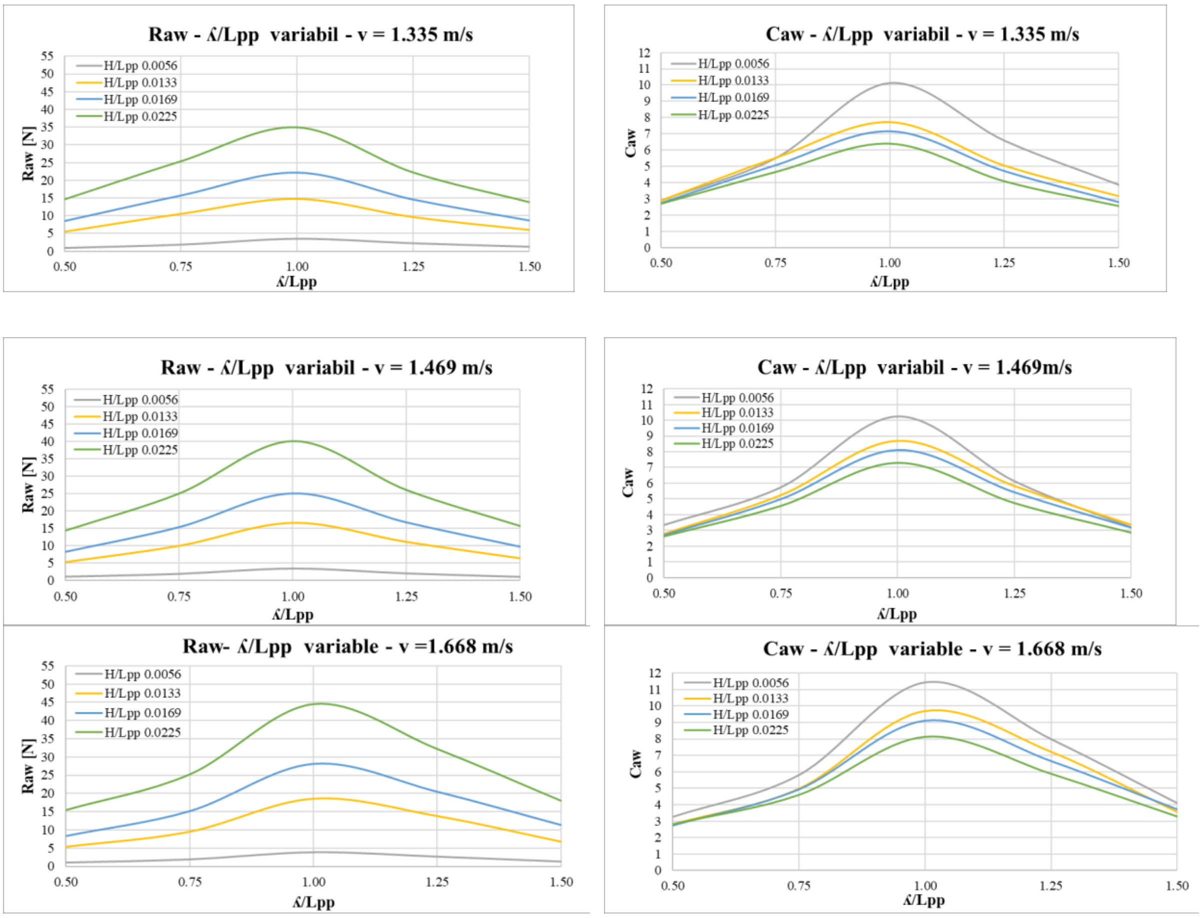


Figure 4.5 Influence of wave length on additional wave resistance and its coefficient [70]

The influence of wave height on added wave resistance and the influence of wave length on RAO Pitch for all six velocities is shown in Figure 4.6. The effect of the wave height for the smallest wave height studied and the highest wave height, considering the adimensional wave length equal to 1, can be seen in Figure 4.7.

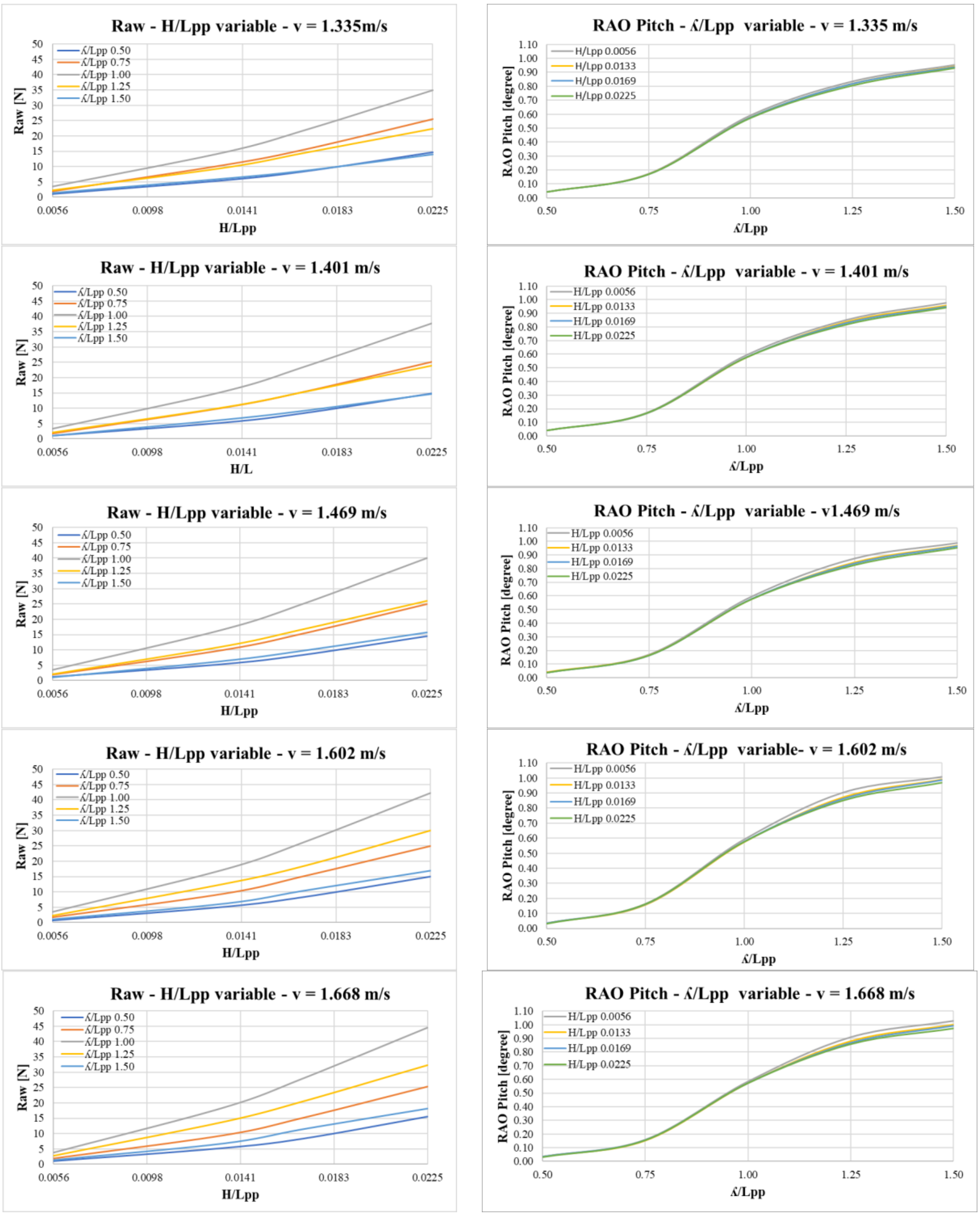


Figure 4.6 Influence of wave length on RAO Pitch and influence of wave height on wave added resistance for the speeds range studied [70]

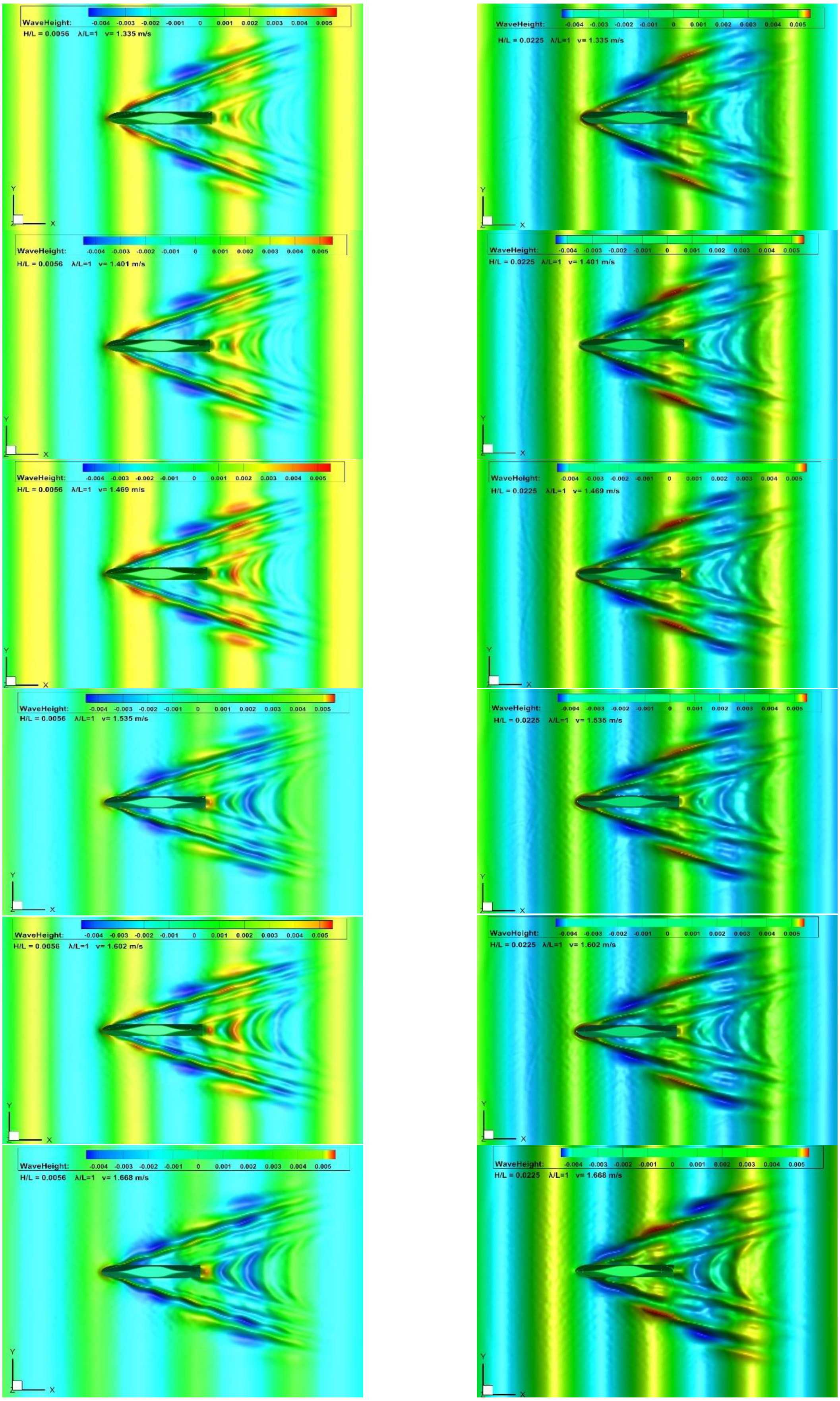


Figure 4.7 Wave height for H/Lpp 0.0056 and H/Lpp 0.0225 [70]

4.6 Irregular waves

Prediction of ship motion in viscous flow under irregular wave conditions (real sea conditions) is very important for seakeeping and ship design [71]. Most of the time, ships operate in irregular waves, and for this reason, the wave resistance must be determined to be able to predict the total resistance developed by the ship.

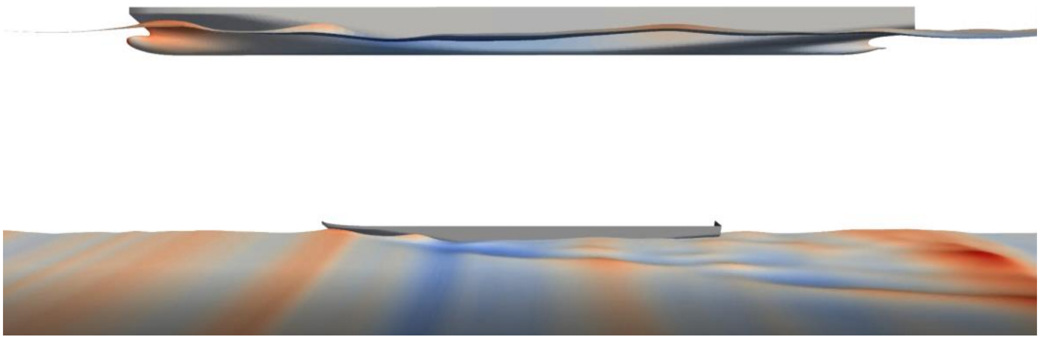
The aim of this study is to investigate the behaviour of the Duisburg Test Case (DTC) container ship in irregular waves for a range of speeds from 20 Knots to 25 Knots and several sea states are shown in Table 4.3.

Table 4.3 Test Cases

Speed, v [Nd]	Sea State
20	2
21	3
22	4
23	5
24	6
25	7
	8

This section presents the results of the irregular wave simulations over the full range of speeds and sea states. Figure 4.8 shows the results for the lowest sea state and higher sea state considered, at speed of 25 Knots.

Sea state 2



Sea state 8

Figure 4.8 Mean wave resistance

4.7 Conclusions

Nowadays, the tendency is to optimize carriers and make conversions on ships already built or to replace old ships with new ones, due to market demand for faster traveling, more fuel-efficient ships that can carry larger loads.

The performances of ships and their operability depend on sailing conditions and therefore on waves. Because of this, a few issues arise that need to be addressed in dealing with the prediction of ship characteristics, such as non-linearities, static pressure, hydrodynamic pressure, interference between waves and hull, and ship response to oscillations.

Thus, in this chapter, a container ship, one of the most popular types of ships for the freight industry, has been studied. Computational fluid dynamics (CFD) numerical simulations were used to determine the ship's behaviour in calm water, regular waves, and irregular waves. This type of method has become a popular option at the expense of basin testing, which has a higher cost, a longer time to obtain a solution, and involves more hull optimization steps.

Resistance in calm water has been validated based on experimental results that are openly published. The determination of the resistance was used following simulations in regular waves to determine the additional resistance in waves. It was observed that wave height and length contributed to the increase in wave resistance. This effect could also be observed through the influence of vessel speed.

Simulations for irregular waves were carried out to determine as accurately as possible the conditions in European seas, so simulations were carried out at full scale and for a range of sea states from 2 to 8.

Therefore, prediction of the ship's motions in waves is necessary to ensure that the ship will operate safely, both for the passengers on board and the ship being carried.

The research presented in this chapter is an extended and updated version of the originally published articles:

1. **Chiroşcă Ana-Maria**, Rusu Liliana, 2021. Comparison Between Model Test and Three CFD Studies for a Benchmark Container Ship, Journal of Marine Science and Engineering, 9 (1), 62. https://doi.org/10.3390/jmse9010062 Impact factor 2,574, Q1.
2. **Chiroşcă Ana-Maria**, Rusu Liliana, 2021. The Use of CFD Methods in the Shipbuilding Industry and their Benefits, AUDOE, Vol. 17, No. 6/2021, pp. 262-269, ISSN: 2065-0175, https://dj.univ-danubius.ro/index.php/AUDOE/article/view/1484
3. **Chiroșcă Ana-Maria,** Rusu Liliana, Păcuraru Florin, 2021. Study on the behavior of benchmark container ships in regular waves, International Conference: Modern Technologies in Industrial Engineering IX (ModTech 2021), June 23-26, Eforie Nord, România, Vol. 1182. https://doi.org/10.1088/1757-899X/1182/1/012013, https://iopscience.iop.org/article/10.1088/1757-899X/1182/1/012013/meta
4. **Chiroșcă Ana-Maria**, Gasparotti Carmen, 2020. Comparison between model test and numerical simulations for a container ship, Proceeding of the 5th International Conference on Maritime Technology and Engineering (Martech2020), Volum Developments in Maritime Technology and Engineering, Editor Francis & Taylor Group, UK, 16-19 November, Lisbon, Portugal, eBook ISBN 9781003216599 https://www.taylorfrancis.com/chapters/edit/10.1201/9781003216599-9/comparison-model-test-numerical-simulations-container-ship-chirosca-gasparotti (indexed Scopus)

CHAPTER 5 – EXPERIMENTAL SIMULATION

5.1 Introduction

Additional wave resistance can be determined by several methods, such as numerical simulations as presented in Chapter 4, and the use of mathematical models or experimental tests. An early method to determine this component was developed by Haverlock [72] in 1937, and then Maruo ([73] to [75]) used momentum conservation theory to find the additional wave resistance based on wave energy. This method was further refined by Joosen [76], Gerritsma, and Beukelman [77]. An improvement of the results was observed in the studies of Salvesen [78] and Korvin-Kroukovsky [79], who added strip theory to these studies, which made this method of determining the additional wave resistance suitable for numerical computation. Over time, strip theory has been developed and improved ([80] to [82]). The main advantage of strip theory is the speed of obtaining sufficiently accurate solutions. A recent study is by Amini-Afshar [83] who, starting from Salvensen's method, used Green's function of the two-dimensional free surface and the lower-order boundary element method.

In this chapter, the results of experimental tests and numerical simulations for the container ship presented in Chapter 4 are presented. A new series of numerical simulations were performed, following the cases from the tests in the basin. The aim was to investigate the response of ship motions for seven wavelengths, three wave heights, and three speeds. In addition, a quadratic study of the added wave drag coefficient was performed.

5.2 Experimental model and set-up

At the "Dunărea de Jos" University of Galati, a model for estimating the additional wave resistance was built at a scale of 1:135 based on the container ship described in Chapter 4. Figure 5.1 depicts the model's various sections after they were 3D printed and in Table 5.2 are presented the main features. The next step was to assemble the sections to create the final hull. The model was created using PLA filament (Polylactic Acid) as the material. The experimental tests were created at the ETSIN – UPM (Escuela Técnica Superior de Ingeniería de Montes, Universidad Politécnica de Madrid) in Madrid.

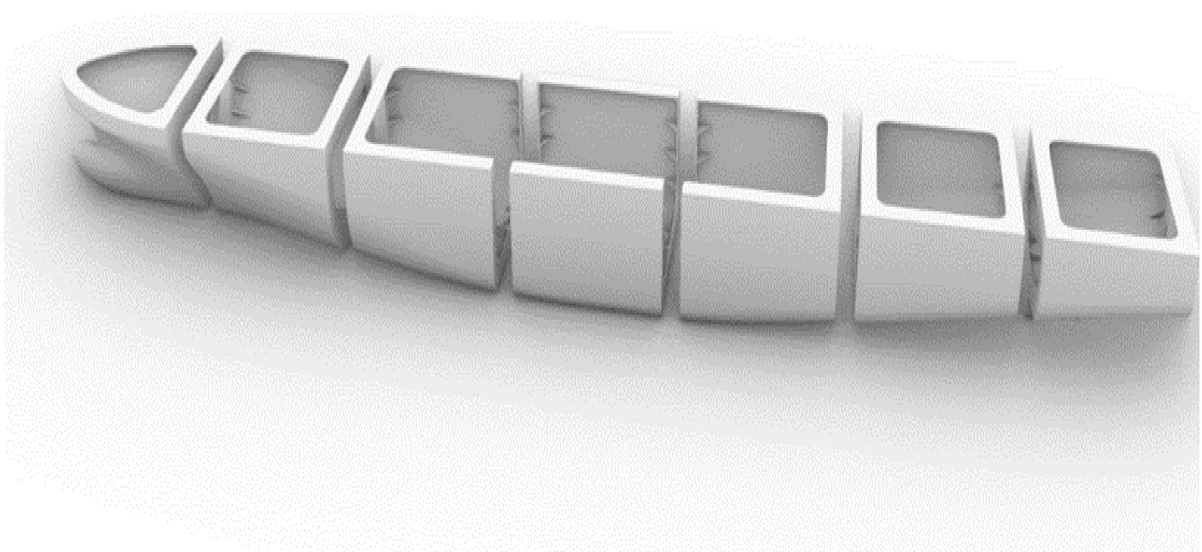


Figure 5.1 DTC model, scale 1:135

Table 5.1 Hull information

Main features		Full-scale	Model-scale
Scale	-	-	135
Length between perpendiculars	m	355	2.630
Waterline breadth	m	51	0.378
Draught midship	m	14.5	0.107
Volume displacement	m^3	173467	0.071
Block coefficient	-	0.661	0.661
Wetted surface	m^2	22032	1.209
Design speed	m/s	12.86	1.107
X_B – measured from the transom	m	-	1.339
X_B – from aft perpendicular	m	-	1.289
Z_B – from baseline	m	-	0.059
X_F – measured the from transom	m	-	1.242
X_G – from aft perpendicular	m	174.059	1.289
Z_G – from aft perpendicular	m	19.851	0.147
ryy	m	87.4	0.647

The complete series of investigations performed in this chapter are presented in Table 5.2.

Table 5.2 Test cases

Type	V [m/s]	λ/L_{PP} [-]	H [m]	T [s]
Calm water	0.664, 0.885, 1.107	----	----	---
Regular waves	0.664, 0.885, 1.107	0.500	0.030, 0.044, 0.057	0.918
	0.664, 0.885, 1.107	0.750	0.030, 0.044, 0.057	1.124
	0.664, 0.885, 1.107	0.875	0.030, 0.044, 0.057	1.214
	0.664, 0.885, 1.107	1.000	0.030, 0.044, 0.057	1.298
	0.664, 0.885, 1.107	1.125	0.030, 0.044, 0.057	1.377
	0.664, 0.885, 1.107	1.250	0.030, 0.044, 0.057	1.451
	0.664, 0.885, 1.107	1.500	0.030, 0.044, 0.057	1.590

5.3 Comparison between experimental results and numerical simulations

This sub-chapter presents the comparison between the results of the experimental test and numerical simulations, as well as the differences between the methods approached. One can see from Figure 5.2 that the results for the calm water resistance are quantitatively comparable, and the flow depicted in Figure 5.3 for each velocity captures the same similarities and non-stationary effects are observed.

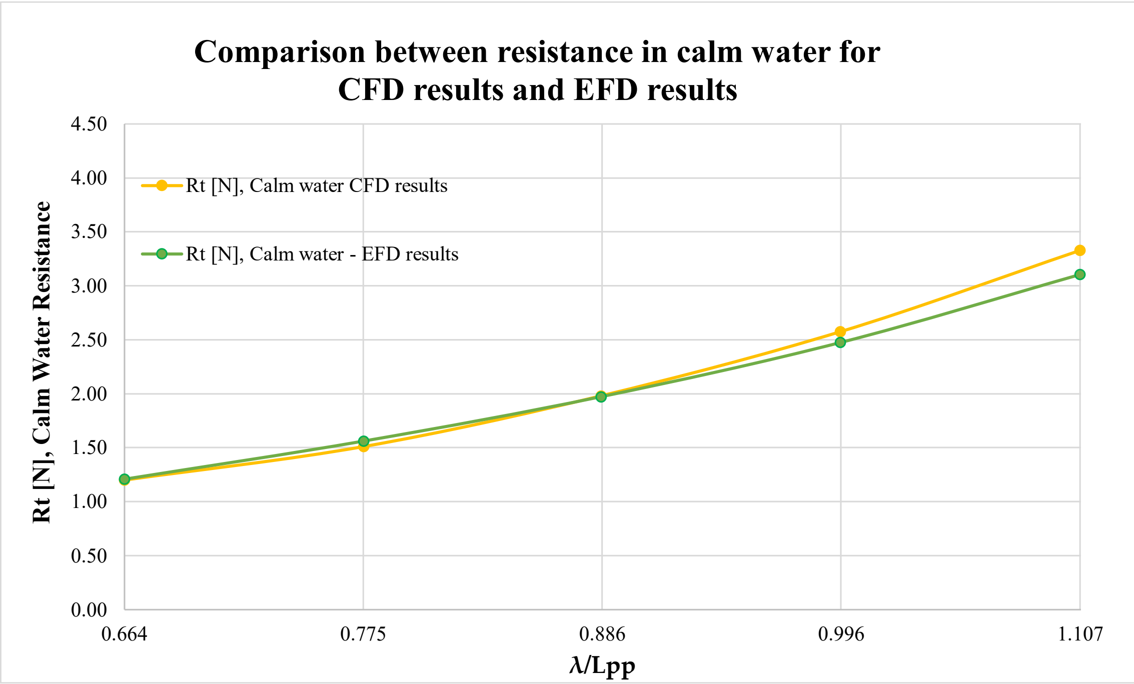
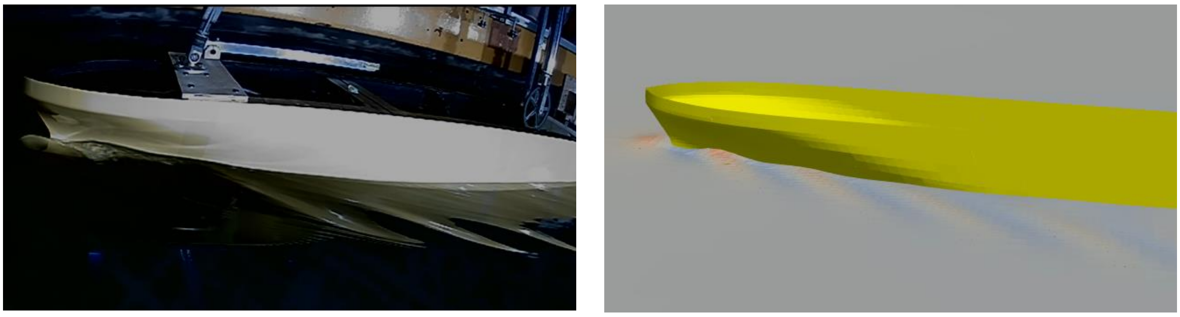
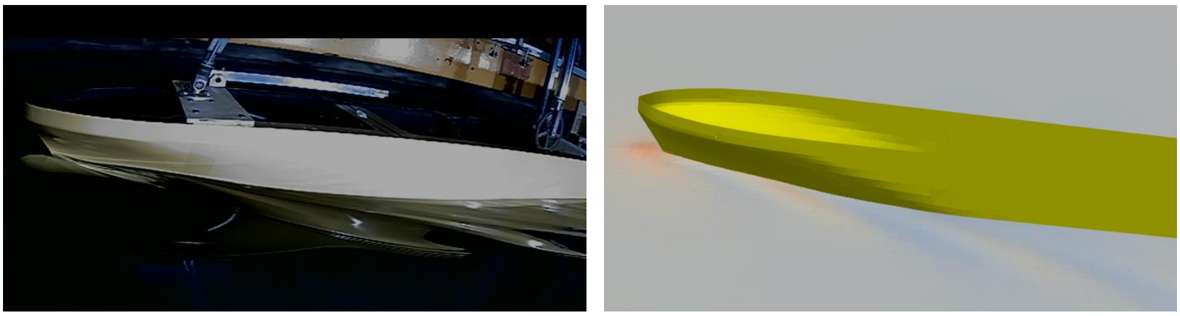


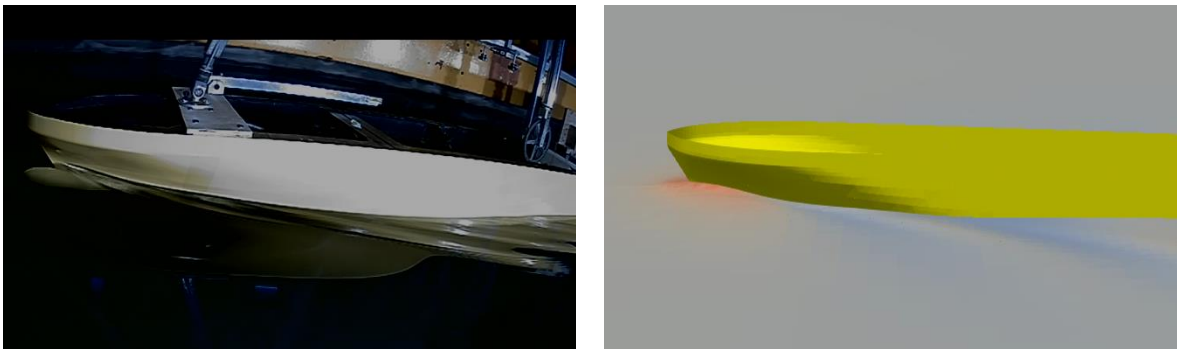
Figure 5.2 Comparison between resistance in calm water



0.664 m/s



0.885 m/s



1.107 m/s

Figure 5.3 Comparison between resistance in calm water for CFD results and EFD results

The differences between the methods were satisfactory when referring to all 3 of the investigated components, additional wave resistance, pitch RAO, and heave RAO, except for the results for the first velocity, where during the experimental test, two peaks were observed along the curves for each wave height studied. The variations between the investigated approaches are highlighted in Figure 5.4.

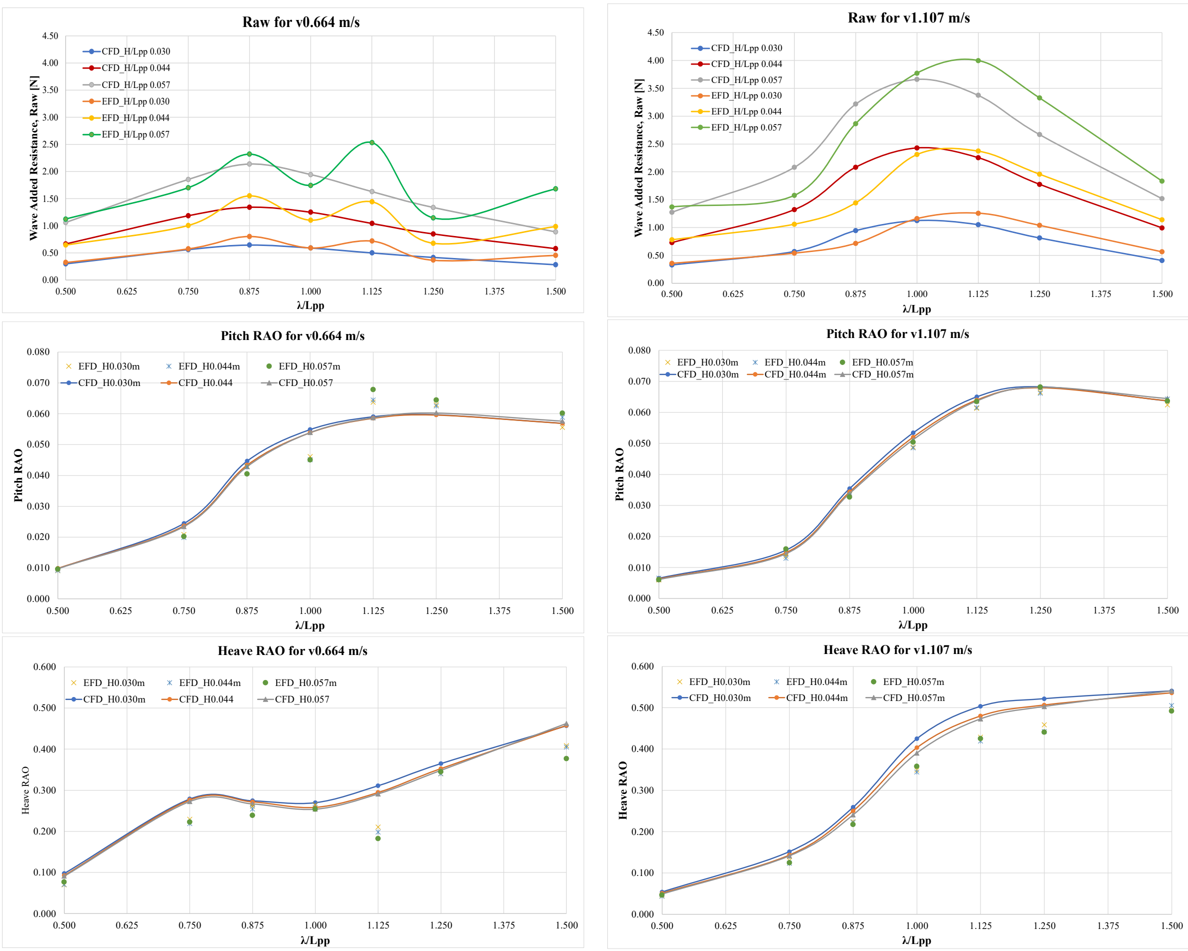
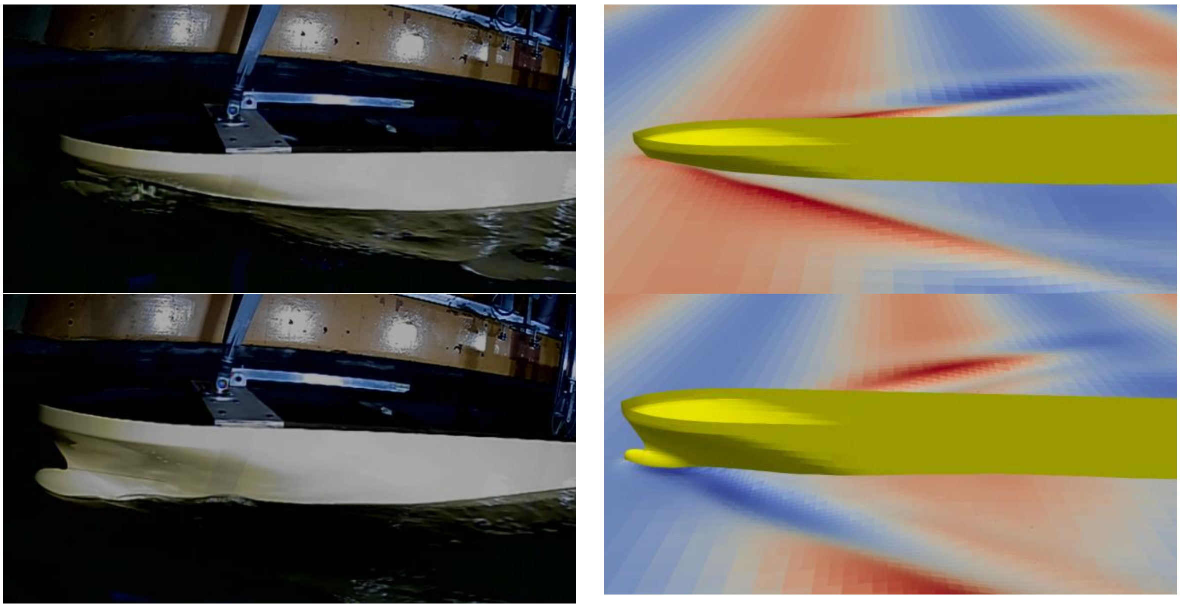
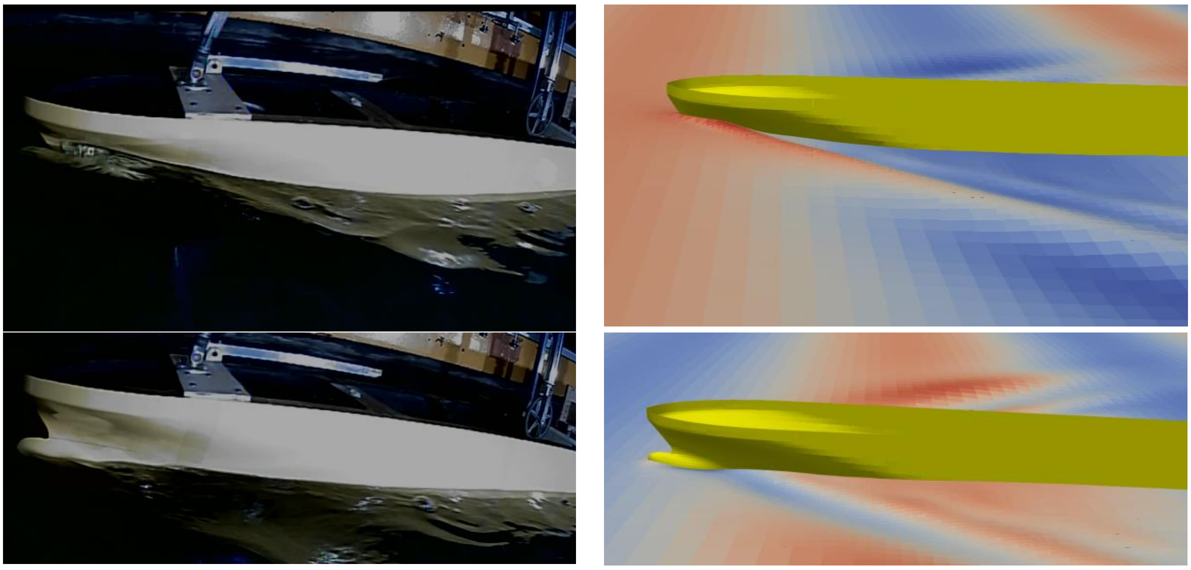


Figure 5.4 Comparison between wave added resistance coefficient, Pitch RAO, and Heave RAO for the lowest and highest speed

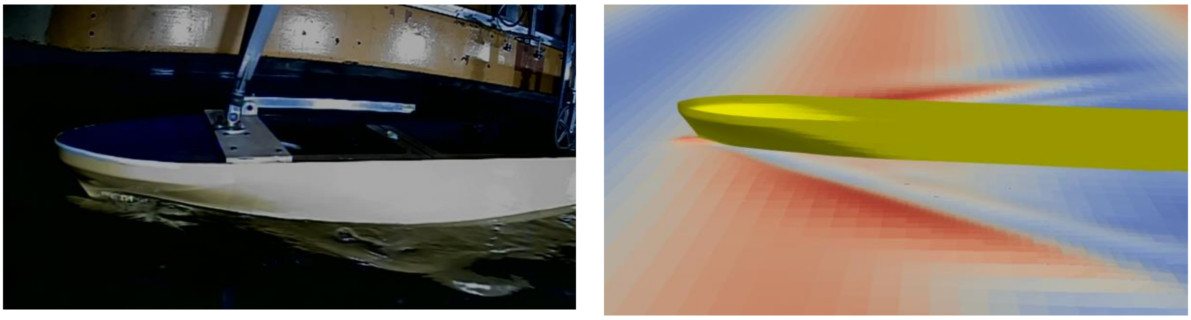
The nonlinear behavior of the bow wave is one feature that can affect the added drag as the bow region of a vessel appears to be the main contributor to the added drag [84]. The bow area behaviors for the wave gaps and wave crest at the identified wavelengths for the two places maximum points, as well as at the intermediate wavelength, were captured in Figure 5.5 .

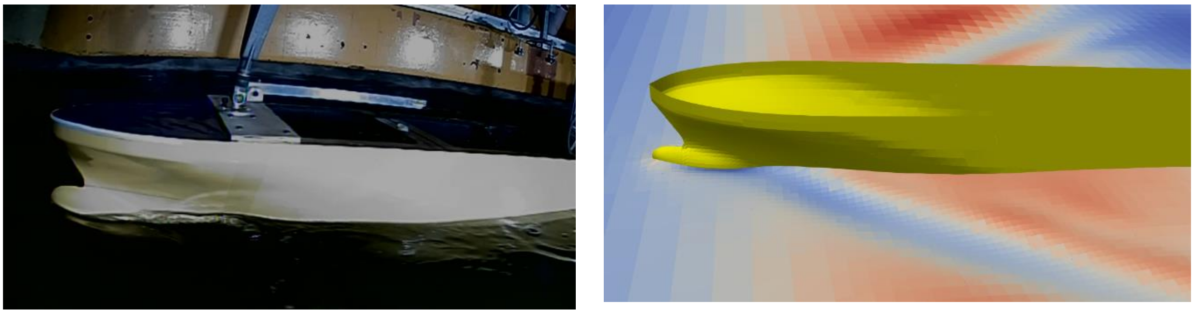


λ/Lpp 0.875 - 0.664 m/s



λ/Lpp 1.000 - 0.664 m/s





λ/Lpp 1.125 - 0.664 m/s

Figure 5.5 Difference between experimental test and numerical simulations

To ascertain whether the double pick observed on the additional resistance coefficient curve could be connected to a change in the kind or intensity of bow wave breaking, a comparable qualitative analysis of the bow wave captured during the tests was carried out.

The steepness of the waves is another aspect that can be seen. As shown in Figure 5.6, the absolute maximum migrates from λ/Lpp = 0.875 at lower steepness to λ/Lpp 1.125 at highest steepness, with an increase in steepness having no effect on the double resonance phenomenon.

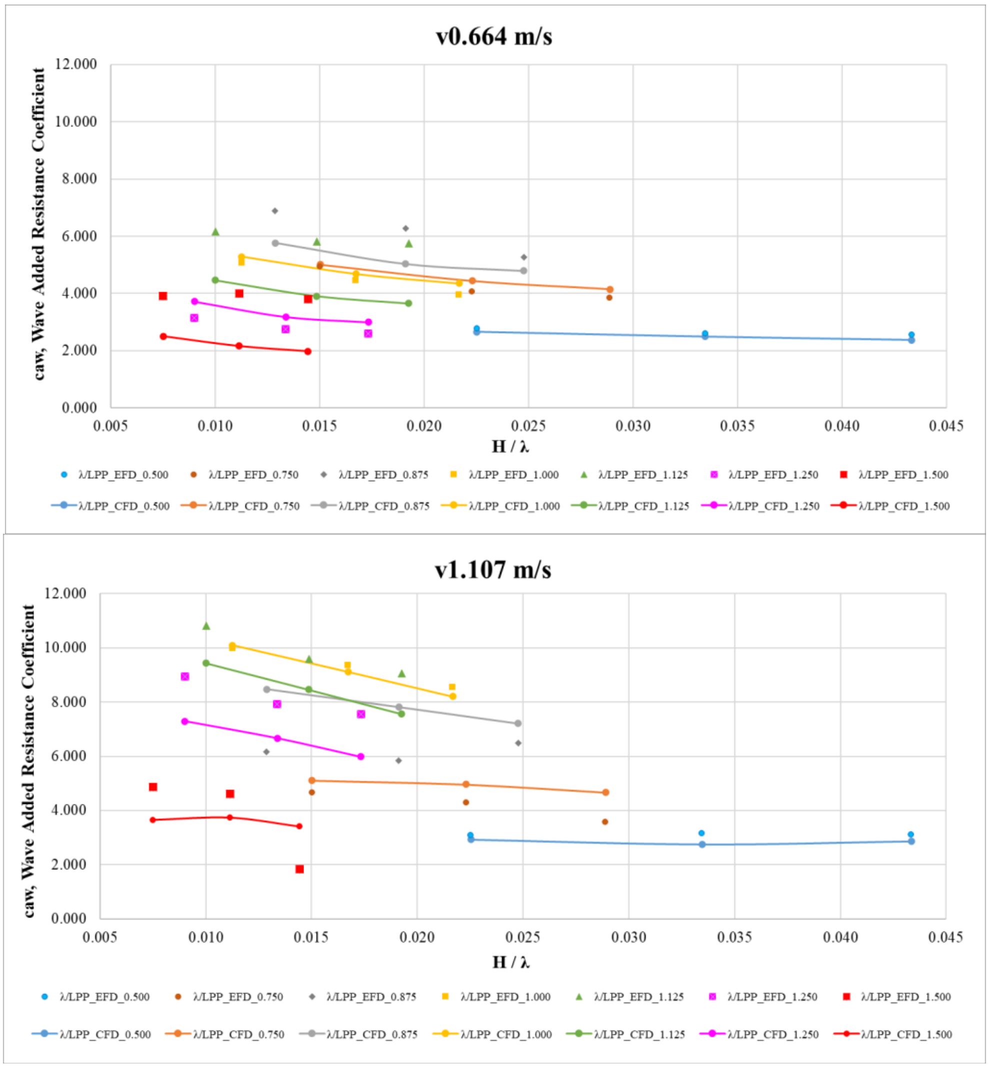


Figure 5.6 Steepness effect for the lowest and highest speed

5.4 Quadratic study on wave added resistance coefficient

The (non-physical) theory for the universal polynomial functional input-output model leads to the idea of a quadratic frequency response function. Tradition methods claims that the additional resistance tends to increase quadratically with wave amplitude. Figure 5.7 displays the additional wave coefficient obtained by increasing the wave height to the 2 and 1.75 powers. By changing the power from 2 to 1.60 with a step of 0.5, it was possible to reach the optimal power of 1.75 at which this effect is captured.

This pattern, presented in Figure 5.7, which is more obvious in the short wavelength range, shows that the additional resistance is not proportional to the square of the wave height. The breaking of incident waves at the bow is assumed to be the source of this event, which results in a loss of wave energy.

According to the results, the added resistance of the vessel is not proportional to the wave height but rather increases at a lower rate than the wave height.

Figure 5.7 Added wave resistance coefficient, quadratic study

5.5 Conclusions

The findings of a research on the additional wave resistance experienced by container ships in typical head waves are presented in this chapter. Accurately calculating the additional resistance in waves is crucial to estimating the ship's speed in the actual sea. Usually, the effect of wave reflection is added to the additional resistance brought on by ship motion. Research into analytical, numerical, and (semi-)empirical techniques for forecasting wave added resistance is continuing. The effect of wave reflection is typically added to the additional resistance brought on by ship motion.

The ship motion response and the additional resistance in waves on the DTC hull were examined by a series of tank towing experiments and computer simulations in this direction. Tests were conducted in both calm water and a head sea in the ETSIN-UPM towing tank. On this facility, numerous experiments were run to assess the level of uncertainty. The direct pressure integration approach was used to calculate the additional wave resistance on the DTC hull in the numerical analysis, which used a 3D fully nonlinear method based on time domain and Rankine panels.

As a numerical tool, the SHIPFLOW commercial software package was employed. For the numerical and experimental experiments, a combination of seven wavelengths, three wave heights, and three velocities was considered. The outcomes were then use for validation in order to learn more about the computational power of the potential-based numerical models that were being used.

Finally, the non-quadratic behavior of the increased drag coefficient and wave amplitude received special attention.

When nonlinear phenomena are present, the accuracy of the numerical analysis cannot be guaranteed. Consequently, it may be an advisable if experimental data can support the numerical evaluation.

Comparisons demonstrated a generally favourable agreement between computations and measurements, except for the double resonance phenomenon at the lowest speed investigated. The 3D fully non-linear time-domain-based Rankine panel method was efficient and effectively compromised accuracy and computer time. However, the method was not able to capture all non-linear phenomena.

An interesting double resonance effect on the wave-added resistance curve has been found at V=0.664 m/s corresponding to a Froude number of 0.13. In this case, the added-resistance curve showed two local maxima, one at λ/LPP = 0.875 and the other at 1.125, that are more significant with the increase of the wave steepness. An in-depth systematic analysis of the recordings made during the experiments led to the conclusion that no significant change of the bow wave can prove the drop of the wave-added resistance at λ/LPP equal to 1.0.

Experimental measurements and CFD study conducted on DTC hull in the present research proved that the effectiveness of linear theory in predicting added resistance may be limited since the commonly used added resistance coefficient reduces with an increase in wave steepness. Changing the power of the wave amplitude to 1.75 in the wave-added resistance coefficient expression improved the correlation between wave height and wave-added resistance.

Further investigations will focus on a more in-depth analysis of the occurrence cause of the double resonance phenomenon based on the experiments conducted around a speed of 0.664 m/s and unsteady RANS computations.

The research presented in this chapter is an extended and updated version of the originally published articles:

1. **Chiroşcă Ana-Maria**, Antonio Medina, Florin Pacuraru, Simone Saettone, Liliana Rusu, Sandita Pacuraru. 2023. Numerical and Experimental Investigation on Wave Added Resistance in Regular Head Waves for DTC Hull submitted in Journal of Marine Science and Engineering

CHAPTER 6 - CONCLUSIONS

6.1 General conclusions

Europe has a long history of shipping, and it presently possesses the largest fleet in the world, with about half of all tonnage. International as well as intra-European shipping is made possible by marine and inland channel transportation. Everything is transported by ship, often over distances of thousands of kilometres, including gas, oil, grain, food, clothing, toys, furniture, and automobiles and many others.

With so many advantages over conventional transportation, shipping is extremely popular. The ability to move large amounts of goods and its low cost are this form of transportation's key benefits.

Marine transport is also considerably more environmentally benign than air, road, and rail transportation. Even further expansion in this form of transportation may be possible with the advancement of technology in the market for waterborne transportation and the replacement of the current fleet with ships capable of carrying more cargo and traveling faster. The decrease of gas emissions and fuel consumption by ships is another factor to be considered to increase the environmental friendliness of canal traffic. Optimizing traffic flow can also cut down on expenses such port fees and lost time when a ship is forced to wait for another ship to pass or is immobile.

The shipbuilding sector has a substantial influence on economic and technological developments in the European maritime basin, as regards the maritime movement of goods and people. Even though the COVID-19 pandemic crisis and the war between Ukraine and Russia have hampered passenger transport, cargo transport has nevertheless increased due to strong market demand. For these reasons, it is important to look at the way shipping is done and the problems it faces, both to optimise it so that we can benefit from it as much as possible and to prevent the many maritime accidents.

The assessment of maritime traffic and ship behaviour in European seas is the main goal of the PhD thesis. For each division of the European seas, the intensity of maritime traffic, the types of ships, and the issues they encounter have been researched. For the major shipping routes in Europe, the wind and wave climate were determined. These findings were related to a container ship's behaviour in calm water, regular waves, and irregular waves.

Weather conditions, particularly wind and wave parameters, are one of the major elements impacting shipping. Knowledge of the wind and wave climate is another crucial factor. It helps to lower accident rates in locations that are vulnerable to severe weather, as well as in coastal areas where there is more congestion, less room for manoeuvres, and shallower water.

When it comes to vessel design, it is necessary to study and assess the hydrodynamic characteristics of the vessel from the basic design before moving on to the subsequent design processes. Solving the complicated and challenging issue of ship hydrodynamics typically involves either empirical methods, numerical simulations, or experimental test.

The most typical ship type in European seas, the container ship, was the subject of numerical models and practical experiments in this study to examine how it behaved in both calm and waves.

One of the elements that significantly affects the overall resistance is the additional wave resistance. Assessing the environmental performance of ships and developing solutions to lessen shipping's negative effects on the environment can be done by evaluating the effect of additional resistance on energy consumption. The ship's route and speed can be optimized to save fuel consumption by predicting the additional wave resistance.

Although regular waves in the water are good for sailors, irregular waves are more common and have a considerably bigger effect on overall strength. To properly forecast ship behaviour, it should be investigated what sea state each route in Europe has. Because ships move at a speed of nearly 10 knots in the port region and the channel area, investigations should also be performed at lower speeds. One of the thesis's potential future directions is this inquiry.

Therefore, shipping is and will continue to be a significant segment of trade both inside and outside of Europe, and the sector is continually evolving and improving to provide the most effective transit.

6.2 Own Contributions

- Research on maritime traffic in European seas;
- Analysis of the water and wave characteristics in European seas ;
- Research on the various types of ships that go through European seas and identification of the major ship types;
- Identification of the most common types of transport vessels;
- Study on characteristics of wind and wave climate;
- Numerical simulations on a container ship in calm water and waves;
- Experimental test for a container ship in calm water and waves.

6.3 Directions for Future Research

- Including a range of slower speeds that are specific to port areas and channels in the analysis of the container ship in irregular waves;
- Examining additional issues that transport vessels may experience, such as manoeuvring, slamming, slamming, green water incidents, and more;
- Improvement of sea routes in European waters to reduce fuel use and, consequently, carbon emissions ;
- Investigation on the wind farms near port areas.

6.4 List Of the Scientific Papers elaborated by the author

A1 Papers published in ISI journals

1. **Chiroșcă Ana-Maria**, Rusu Liliana, Bleoju Anca, 2022. Study on wind farms in the North Sea area, Energy Reports, Volume 8, Supplement 16, Pages 162-168, ISSN 2352-4847,https://doi.org/10.1016/j.egyr.2022.10.244, Impact factor 4,937
2. **Chiroșcă Ana-Maria**, Rusu Liliana, 2022. Characteristics of the wind and wave climate along the European seas focusing on the main maritime routes, *Journal of Marine Science and Engineering,* 10(1), 75. https://doi.org/10.3390/jmse10010075 Impact factor 2,574, Q1
3. **Chiroșcă Ana-Maria**, Rusu Liliana, 2021. Comparison Between Model Test and Three CFD Studies for a Benchmark Container Ship, *Journal of Marine Science and Engineering*, 9 (1), 62. https://doi.org/10.3390/jmse9010062 Impact factor 2,574, Q1

A2 Papers published in BDI journals

1. **Chiroşcă Ana-Maria**, Rusu Liliana, 2021. The Characteristics of the North Sea and its Importance for Maritime Transport, AUDOE, Vol. 17, No. 6/2021, pp. 224-229, ISSN: 2065-0175, https://dj.univ-danubius.ro/index.php/AUDOE/article/view/1481

2. **Chiroşcă Ana-Maria**, Rusu Liliana, 2021. The Use of CFD Methods in the Shipbuilding Industry and their Benefits, AUDOE, Vol. 17, No. 6/2021, pp. 262-269, ISSN: 2065-0175, https://dj.univ-danubius.ro/index.php/AUDOE/article/view/1484

3. **Chiroşcă Ana-Maria**, Rusu Liliana, 2021. Statistical and Economic Analysis of the Rhine-Main-Danube Canal, the Bridge Between the North Sea and the Black Sea, Journal of Danubian Studies and Research, Vol. 11, No. 1/2021, pp. 184-191, ISSN 2284-5224, https://dj.univ-danubius.ro/index.php/JDSR/article/view/1288/1491

4. **Chiroşcă Ana-Maria**, Rusu Liliana, 2021. Study on Navigation Conditions and Shipping Traffic on the Danube in the Period 2010-2020, Journal of Danubian Studies and Research, Vol. 11, No. 1/2021, pp. 192-201, ISSN 2284-5224, https://dj.univ-danubius.ro/index.php/JDSR/article/view/1301/1490

5. **Chiroşcă Ana-Maria**, Rusu Liliana, 2019. Marine Traffic on Mediterranean Seas and its divisions, *Mechanical Testing and Diagnosis*, Volume 4, pp. 11-18, ISSN 2247 – 9635, 2019 (IX) https://doi.org/10.35219/mtd.2019.4.02

A3 Papers published in the volumes of international conferences

1. **Chiroşcă Ana-Maria**, Rusu Liliana, 2022. Study of climate changes and their impact on maritime transport in the Black Sea area, Proceedings of 22nd International Multidisciplinary Scientific GeoConference SGEM 2022, Volume 22, Issue 3.1. https://doi.org/10.5593/sgem2022/3.1/s12.22

2. **Chiroşcă Ana-Maria**, Rusu Liliana, 2021. The Economic Importance of Navigation Along the Danube-Black Sea Channel, presented at XXIth International Multidisciplinary Scientific GeoConference Surveying, Geology and Mining, Ecology, and Management – SGEM 2021, 14 -22 August, Albena, Bulgaria, Volume 21, 3.1, pages 297-306. https://doi.org/10.5593/sgem2021/3.1/s12.45

3. **Chiroșcă Ana-Maria**, Rusu Liliana, Păcuraru Florin, 2021. Study on the behavior of benchmark container ships in regular waves, International Conference: Modern Technologies in Industrial Engineering IX (ModTech 2021), June 23-26, Eforie Nord, România, Vol. 1182. https://doi.org/10.1088/1757-899X/1182/1/012013, https://iopscience.iop.org/article/10.1088/1757-899X/1182/1/012013/meta
4. **Chiroșcă Ana-Maria**, Rusu Liliana, 2020. Statistical analysis of the types of ships that have crossed the European ports in the last decade. 20th SGEM International Scientific Conferences on Earth & Planetary Sciences, Extended Scientific Sessions „GREEN SCIENCE FOR GREEN LIFE" SGEM Vienna GREEN 8-11 December 2020, Vol. 20, 249-256, ISBN 978-619-7603-17-0. https://doi.org/10.5593/sgem2020V/1.3/s02.31
5. **Chiroșcă Ana-Maria**, Gasparotti Carmen, 2020. Comparison between model test and numerical simulations for a container ship, Proceeding of the 5th International Conference on Maritime Technology and Engineering (Martech2020), Volum Developments in Maritime Technology and Engineering, Editor Francis & Taylor Group, UK, 16-19 November, Lisbon, Portugal, eBook ISBN 9781003216599 https://www.taylorfrancis.com/chapters/edit/10.1201/9781003216599-9/comparison-model-test-numerical-simulations-container-ship-chirosca-gasparotti
6. Vazdoaga, I., **Chirosca, A.**, Rusu, L., Popa, V. -I., 2020. Extreme phenomena on Danube hydrodynamics and the influence on the navigation conditions, 20th International Multidisciplinary Scientific GeoConference SGEM 2020, 18 - 24 August 2020, Vol. 20, 123-130, ISBN:978-619-7603-08-8 https://doi.org/10.5593/sgem2020/3.1/s12.016 (indexed Scopus)
7. **Chiroșcă Ana-Maria**, Rusu Liliana 2020. Sea state characteristics and the maritime traffic in the European seas, 20th International Multidisciplinary Scientific GeoConference SGEM, 18 - 24 August, Vol. 20, 1314-2704, ISBN:978-619-7603-08-8, https://doi.org/10.5593/sgem2020/3.1/s15.111 (indexed Scopus)

A4 Papers presented at national conferences with international participation

1. **Chiroșcă Ana-Maria**, Rusu Liliana, „Numerical Simulations on Irregular waves for a container ship" presented 10th edition of the Scientific Conference organized by the Doctoral Schools of "Dunărea de Jos" University of Galați (SCDS-UDJG), 9-10 June 2022, Galați, România (award-winning presentation – first prize)
2. **Chiroșcă Ana-Maria**, Dănilă (Vâzdoagă) Ionela, Rusu Liliana, Popa Victor-Ionuț, Navigation conditions and restrictions along the Danube-Black Sea channel, presented at 9th edition of the Scientific Conference organized by the Doctoral Schools of "Dunărea de Jos" University of Galați (SCDS-UDJG), 10-11 June 2021, Galați, România
3. **Chiroșcă Ana-Maria**, Rusu Liliana, Evaluation of the maritime traffic, accidents and causalities in the European seas, presented at 9th edition of the Scientific Conference organized by the Doctoral Schools of "Dunărea de Jos" University of Galați (SCDS-UDJG), 10-11 June 2021, Galați, România
4. **Chiroșcă Ana-Maria**, Rusu Liliana, Analysis of the wave and wind conditions along the European seas for the last twenty years, presented at 9th edition of the Scientific Conference organized by the Doctoral Schools of "Dunărea de Jos" University of Galați (SCDS-UDJG), 10-11 June 2021, Galați, România (award-winning presentation)
5. **Chiroșcă Ana-Maria**, Dănilă (Vâzdoagă) Ionela, Rusu Liliana, Popa Victor-Ionuț, 2020. Danube Hydrodynamics and Navigation Traffic, presented at the 8th edition of the Scientific Conference organized by the Doctoral Schools of "Dunărea de Jos" University of Galați (SCDS-UDJG), 18-19 June 2020, Galați, România.

6. **Chiroșcă Ana-Maria**, Rusu Liliana, Marine Traffic on Mediterranean Seas and its Divisions, presented at the 8th edition of the Scientific Conference organized by the Doctoral Schools of “Dunărea de Jos” University of Galați (SCDS-UDJG), 18-19 June 2020, Galați, România
7. **Chiroșcă Ana-Maria**, Rusu Liliana, Comparison Between Model Test and Three CFD Studies for a Benchmark Container Ship presented at 8th edition of the Scientific Conference organized by the Doctoral Schools of “Dunărea de Jos” University of Galați (SCDS-UDJG), 18-19 June 2020, Galați, România (award-winning presentation)

A5 Projects

1. **ANTREPRENORDOC**, in the framework of Human Resources Development Operational Programme 2014-2020, financed from the European Social Fund under the contract number 36355/23.05.2019 HRD OP /380/6/13 – SMIS Code: 123847
2. Research project **CLIMEWAR** (CLimate change IMpact Evaluation on future WAve conditions at Regional scale for the Black and Mediterranean seas marine system), supported by the Romanian Executive Agency for Higher Education, Research, Development and Innovation Funding – UEFISCDI, grant number PN-III-P4-PCE-2021-0015.

A6 Awards

1. Diploma of Excellence for excellent results in research activity within IOSUD-UDJG in 2022, CEREX Gala.
2. Award I for the paper: *Numerical Simulations on Irregular waves for a container ship* presented 10th edition of the Scientific Conference organized by the Doctoral Schools of “Dunărea de Jos” University of Galați (SCDS-UDJG), 9-10 June 2022, Galați, România
3. Diploma of Excellence for excellent results in research activity within IOSUD-UDJG in 2021, CEREX Gala.
4. Award II for the impressive presentation of the paper: Study on the behavior of benchmark container ships in regular waves at ModTech 2021, International Conference, June 23-26, Eforie Nord, România
5. Award for the article "Comparison Between Model Test and Three CFD Studies for a Benchmark Container Ship" in the PRECISI 2021 Competition, Award of Research Results - Articles by UEFISCDI, September, 2021.
6. Award II for presentation of the paper*: Evaluation of the maritime traffic, accidents, and causalities in the European seas* at 9th edition of the Scientific Conference organized by the Doctoral Schools of “Dunărea de Jos” University of Galați (SCDS-UDJG), 10-11 June 2021, Galați, România
7. Award III for presentation of the paper: *Comparison Between Model Test and Three CFD Studies for a Benchmark Container Ship* at 8th edition of the Scientific Conference organized by the Doctoral Schools of “Dunărea de Jos” University of Galați (SCDS-UDJG), 10-11 June 2020, Galați, România

A7 Papers submitted in the evaluation stage

1. **Chiroşcă Ana-Maria**, Antonio Medina, Florin Pacuraru, Simone Saettone, Liliana Rusu, Sandita Pacuraru. 2023. Numerical and Experimental Investigation on Wave Added Resistance in Regular Head Waves for DTC Hull submitted in Journal of Marine Science and Engineering

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