D.T1.3.1 - Multimodal safest path algorithm design report

Version n. 1.00

Subtitle **12/2023**

Summary

LIST OF TABLES

There is no table in the document

LIST OF FIGURES

LIST OF ACRONYMS

ADRIREP - Mandatory ships reporting system in the Adriatic Sea

AIS – Automatic Identification System

AMSPM - Administration for Maritime Safety and Port Management of Montenegro

ASL - Above Sea Level

ASTERIX - All-Purpose Structured Eurocontrol Surveillance Information Exchange

ATA - Actual Time of Arrival

AtoN - Aids to Navigation

BC - Beneficiary Country

BoQ - Bill of Quantity

BS - Base Station

CA - Contracting Authority

CAMP - Coastal Area Management Programme

CBC – Cross border cooperation

CS - Coastal Station

CCTV - Closed Circuit TV

DB - Database

DF - Direction Finding

DGNSS – Differential Global Navigation Satellite System

DGPS - Differential Global Positioning System

EC – European Commission

ECDIS - Electronic Charts Display and Information System

EEZ - Exclusive Economic Zone

EMSA – European Maritime Safety Agency

ETA - Estimated Time of Arrival

ETD - Estimated Time of Departure

ENI - European Neighbourhood Instrument

EU – European Union

FAL - Convention on Facilitation of International Maritime Traffic

GMDSS - Global Maritime Distress and Safety System

GIS - Geographic Information System

GHG - Greenhouse gas

GPS - Global Positioning System

HAZMAT - Dangerous and Polluting Goods

HM - Harbour Master

IALA - International Association of Marine Aids to Navigation and Lighthouse Authorities

ICG - Italian Coast Guard

IMDG - International Maritime Dangerous Goods

IMO - International Maritime Organization

IMS - Integrated Maritime Services

IPA II - Instrument for Pre-Accession II

ISPS - International Code for the Security of Ships and of Port Facilities

ITOPF - The International Tanker Owners Pollution Federation Limited

IVEF - Inter VTS Exchange Format

LRIT - Long Range Information and Tracking system

MAREΣ – Mediterranean Regional AIS server

MARPOL - International Convention for the Prevention of Pollution from Ships

MEPC - Marine Environment Protection Committee

MMSI – Maritime Mobile Service Identities

MPA – Marine Protected Areas

MRCC - Maritime Rescue Coordination Centre

MTTR - Mean time to repair

N.A. - Not Applicable

NAS - Navigational Assistance Service

NAIS - National Agency for Information Society

NCA – National Competent Authority

NM - Nautical Miles

OPRC - International Convention on Oil Pollution Preparedness, Response and Cooperation

OSD - Oil Spill Detection

PCS - Port Community System

PFSO - Port Facility Security Officer

PMC - Port Monitoring Centre

PSSA - Particularly Sensitive Sea Area

PS - Port State

PSC - Port State Control

RF - Radio Frequency

SafeSeaNet - Vessel traffic monitoring in EU waters

SAR - Search and Rescue

SOLAS - Safety of Life at Sea SP State Police

SAR - Synthetic Aperture Radar or Search and Rescue

SLA – Service Level Agreement

SSL - Secure Sockets Layer

TBC - To Be Confirmed

UPS - Uninterruptible Power Supply

VHF - Very High Frequency

VoIP - Voice over Internet Protocol

VPN - Virtual Private Network

VTMIS - Vessel Traffic Monitoring and Information Services

VTS - Vessel Traffic Services

WAN - Wide Area Network

WMS - Web Mapping Services

XML - eXtensible Markup Language

1. INTRODUCTION

In an interconnected world where maritime commerce serves as the lifeblood of global trade, the challenge of efficiently navigating commercial routes while ensuring the safety of both cargo and the environment has never been more critical, with a specific concern on the transportation of hazardous materials across vast expanses of the ocean. The quest to find the shortest and safest path for maritime commercial routes carrying dangerous cargo has become paramount, demanding the convergence of advanced technology, planning, and a profound understanding the balance between economic viability and environmental preservation.

As societies continue to rely on the seamless movement of goods across continents, including transporting hazardous materials. These materials, which include chemicals, flammable substances, and other potentially harmful cargo, present a unique set of challenges that necessitate careful consideration at every stage of their journey. The potential consequences of accidents or mishandling in maritime transportation are far-reaching, encompassing the safety of crew members and vessels and the ecological health of oceans and coastlines that serve as our planet's ecological backbone.

Between economic imperatives and environmental stewardship, the central question emerges: How can we optimize maritime routes for vessels transporting dangerous materials, ensuring both the swiftness of delivery and the protection of marine ecosystems? This multifaceted inquiry requires an interdisciplinary approach with cutting-edge navigational technologies, risk assessment methodologies, and international regulatory frameworks. From advanced route planning algorithms that factor in weather patterns, traffic density, and proximity to sensitive ecological zones, to real-time monitoring systems that detect deviations from planned routes and respond with timely interventions, the endeavour to find the shortest and safest path for maritime commercial routes carrying dangerous materials is a complex work demanding innovative solutions.

1.1 General Background

Transportation by sea has been a cornerstone of global trade for centuries, facilitating the movement of raw materials, finished products, and commodities across vast distances. As international trade has expanded and evolved, so too have the complexities and challenges associated with maritime transportation. One of the most pressing concerns is the safe and efficient navigation of ships carrying hazardous or dangerous cargo on board.

Hazardous materials encompass a wide range of substances, including chemicals, gases, flammable liquids, and radioactive materials. These materials are vital to various industries, from manufacturing and energy production to agriculture and healthcare. While their transportation is crucial to sustaining modern economies, it also introduces unique risks that demand meticulous planning and execution.

The primary objectives when transporting dangerous materials via maritime routes are to ensure the safety of human life, protect vessels and cargo, and prevent environmental harm. The potential consequences of accidents involving hazardous materials are severe, encompassing immediate threats to crew members, long-term health risks, and environmental degradation. With its delicate balance of flora and fauna, the marine ecosystem is particularly vulnerable to contamination from spills or leaks from ships.

The quest to find the shortest and safest path for maritime commercial routes carrying dangerous materials is complex that requires a comprehensive understanding of factors such as navigational hazards, weather patterns, traffic congestion, and proximity to populated areas or ecologically sensitive zones. Achieving this delicate equilibrium demands a combination of advanced technology, sophisticated risk assessment methods, and a robust legal and regulatory framework that guides maritime operations.

Over the years, advancements in satellite-based navigation, real-time monitoring systems, and predictive modelling have greatly enhanced our ability to plan and execute safer maritime journeys. Innovations such as Geographic Information Systems (GIS) and Automatic Identification Systems (AIS) allow for precise route planning, considering dynamic factors such as weather changes and real-time vessel traffic. Risk assessment methodologies help identify high-risk areas and enable the implementation of preventive measures to mitigate potential incidents.

Furthermore, international conventions and agreements, such as the International Maritime Dangerous Goods (IMDG) Code, provide standardized guidelines for safely transporting hazardous materials by sea. Regulatory bodies and maritime organizations are crucial in setting industry standards, ensuring compliance, and fostering a safety culture among shipping companies and crew members.

The challenge of finding the shortest and safest path for maritime commercial routes carrying dangerous materials is an ongoing endeavour that reflects the intricate interplay between global trade, technological innovation, environmental preservation, and human well-being. It is also important for the Programming Area and countries tries as Albania, Italy and Montenegro, so pursuing optimal navigation solutions remains paramount to achieving a harmonious balance between economic prosperity and environment protection of our marine ecosystems of South Adriatic.

2. OBJECTIVES, BENEFICIARIES, DESCRIPTION OF ASSIGNMENT AND OUTPUTS

This chapter will describe objectives, beneficiaries, and descriptions of assignments and outputs.

2.1 General Objective

The Program Area of Interreg - IPA CBC Italy - Albania – Montenegro[1] is particularly exposed to risks arising from natural and human disasters: desertification, fires, and pollution, are just some examples, to which it must be added the aggression deriving from the processes of economic development that afflict the territory.

The strategic partnership that links Italy to Albania and Montenegro has led, over the years, to the signing of a series of treaties that have created a favourable environment for investments aimed at promoting the stabilization and pacification of the Balkan region, through the development cooperation and territorial promotion, favoured by important trilateral trade and cultural relations in various sectors: energy, manufacturing industries, urban planning, water resources management, environmental reclamation, etc.

So, it is in this perspective that the action of this project is inserted, aimed at mitigating the effects deriving from the disasters caused by the sea multimodal transport of hazardous materials. The most important challenge, therefore, is to develop common policies capable of constantly monitoring the transport of these materials, through the development of systemic cooperation schemes that involve, at various levels, the stakeholders of the participating countries [1].

The main objective of this project is to improve the transportation activities in the programme area, emphasizing the transportation of hazardous materials. In particular, this project will contribute to the specific objective "4.1 Transport" by studying the peculiar risks in the program area and developing novel decision support modules aiming to assist cross-border management of hazardous materials[2].

2.1.1 Specific Objectives

The CRISIS project will contribute to allocating ships carrying hazardous materials to berths based on real-time numerical simulations of weather (wave and wind) conditions. The main outputs of the project will be

[1] https://www.italy-albania-montenegro.eu/index.php/programme/south-adriatic-2021-27/south-adriatic-docs

[2] https://crisis.italy-albania-montenegro.eu/

the identification of specific risk measures capturing the main aspects of hazardous material transportation in the programme area, the design and development of a multimodal safest routing algorithm for dangerous material transportation in the programme area, and the design and development of a berth allocation algorithm for hazardous material transportation in the programme area.

The specific objective of the CRISIS project is to improve the programme area's transportation activities, emphasising the transport of hazardous materials. The project will study the peculiar risks in the programme area, aiming to develop novel decision support modules aiming to assist cross-border management of hazardous materials [1].

2.2 Beneficiaries

The main beneficiaries are listed below:

- Città di Molfetta (IT)[3], Lead partner
- FLAG Molise Costiero[4] (IT), project partner and
- Municipality of Ulcinj[5] (ME), project partner and
- National Environment Agency (AL), associated partner.

However, the benefit from the project will have the whole society in the programming area, where the action is taking place.

2.3 Description of the assignment and tasks

In order to ensure the smooth implementation of the project and tasks, in line with the approved application form, CRISIS project partners have engaged external experts to support the spread of project activities, results, and outputs to the Programme area and beyond.

According to ToR following objectives must be achieved: data collection and analysis of the problems of routing hazardous materials inside the ports, and the surrounding areas, monitoring and supporting passing ships and allocating ships carrying dangerous materials to berths according to the approved Application Form of the project CRISIS „Cross-border RISk management of hazardous material transportation“.

The requested services are divided into four activities and presented below. This deliverable covers the tasks under activity A.T1.3 “Multimodal safest path algorithm design”.

---

3 https://www.comune.molfetta.ba.it/

4 www.Flagmolise.it

5 www.ul-gov.me

2.3.1 Activity A.T1.1 - Data collection and analysis

This activity aims to analyse the problems of routing hazardous materials inside the ports and surrounding areas, monitoring and supporting passing ships and allocating ships carrying dangerous materials to berths [1]. The goal is to identify the peculiar problems and to collect data related to the different ports and areas where the proposed methodologies could be implemented.

This activity performs maritime traffic analysis in the programming area and data related to maritime dangerous cargo transportation in Albania, Italy and Montenegro.

2.3.2 Activity A.T1.2 - Definition of specific risk measures

This activity will define specific risk measures to consider when designing the models and algorithms.

In the frame of this activity, data on previous incidents while handling dangerous cargo in the programming area and Montenegro will be performed. Based on historical data, specific risk measures will be proposed.

2.3.3 Activity A.T1.3 - Multimodal safest path algorithm design

The aim of this activity is to develop models and algorithms to route shipments in the transportation network in such a way that, not only travel cost is reduced, but also transportation risk is minimized. In fact, in order to carry some hazardous goods from an origin to a destination, the path with the minimum travel cost may not always correspond to the minimum-risk route (i.e., the safest path). The models should include explicitly real-time information about the weather and sea conditions.

2.3.4 Activity A.T1.4 - Berth allocation algorithm design

The berth allocation problem aims to optimally assign and schedule ships to berthing areas along a quay. The objective is the depreciation of the total (weighted) service time for all ships, defined as the time elapsed between the arrival in the port and the completion of handling the minimisation activity. It includes the estimate of the downtime due to wave and wind action at a particular berth.

2.4 Required output and deliverables

In the frame of T1 following four deliverables will be prepared and listed and shortly explained in the following subchapters. This document is actually the deliverable D.T1.1.3 described in subchapter 2.4.3.

2.4.1 Deliverable D.T1.1.1 - Data analysis report

A report with a preliminary analysis aimed at making sense of the data collected in order to highlight the peculiarities and critical aspects of hazardous transportation in the programme area.

The desk research is conducted, and data collection is performed on the maritime transport and transport of dangerous cargo in the program area.

2.4.2 Deliverable D.T1.2.1 - Risk measures report

A report on specific risk measures capturing the main aspects of hazardous material transportation in the programme area.

The desk research and data collection will be performed on previous incidents and potential risks during the maritime transport of dangerous cargo in the program area.

2.4.3 Deliverable D.T1.3.1 - Multimodal safest path algorithm design report

A report on designing the multimodal safest routing algorithm for hazardous material transportation in the programme area.

The results will be presented in this deliverable.

2.4.4 Deliverable D.T1.4.1 - Berth allocation algorithm design report

A report on the design of the berth allocation algorithm for hazardous material transportation in the programme area.

3. THE PROBLEM OF FINDING THE SHORTEST AND SAFEST MARITIME ROUTE FOR DANGEROUS CARGO

In today's interconnected world, maritime trade serves as the lifeblood of global economies, facilitating the transportation of goods and resources on an unprecedented scale. However, it brings a complex set of challenges, including the transportation of hazardous or dangerous cargo across the world's seas and oceans. The safe and efficient navigation of ships carrying such volatile materials has become a critical concern, necessitating a profound understanding of maritime routes, risk management, and technological advancements.

Economic imperatives and environmental preservation have thrust the quest for the shortest and safest maritime route for ships carrying dangerous cargo into the spotlight. This multifaceted problem requires a delicate balance between optimizing transit times and safeguarding human lives, fragile ecosystems, and vital coastal communities. The dynamic interplay of factors such as vessel size, cargo type, weather patterns, geopolitical considerations, and the evolving landscape of maritime regulations further intensifies the issue's complexity.

In recent years, technological advancements, including real-time satellite monitoring, predictive analytics, and artificial intelligence, have revolutionised the maritime industry's route planning and risk assessment approach. These tools can enhance decision-making processes by providing captains, shipowners, and regulatory authorities with actionable insights into optimal routes that minimize exposure to potential hazards while maximizing efficiency.

This exploration into the problem of finding the shortest and safest maritime route for ships carrying dangerous cargo encompasses a broad spectrum of disciplines, ranging from maritime navigation and logistics to environmental protection and international law. It makes challenges to harmonize the imperatives of commerce and safety, fostering innovation and collaboration to address the evolving demands of a globalized world.

This report explores the multifaceted dimensions of this intricate challenge, offering insights into the technological, logistical, regulatory, and ethical considerations underpinning the endeavour to navigate the seas with prudence and responsibility. By illuminating the complexities of this problem, the aim is to contribute to the safe passage of ships carrying dangerous cargo across the South Adriatic.

Approaching the problem of finding the shortest and safest maritime route requires careful consideration of multiple factors:

- avoiding dangerous weather conditions and navigation around maritime protected areas,
- identifying areas prone to severe weather conditions (such as storms etc.),
- respecting maritime protected areas
- minimise fuel consumption,
- whale & ice-avoidance navigation algorithms (not applicable in the Programming Area)

In the next subchapters, some of the problems will be elaborated in more detail.

3.1 Avoidance of dangerous weather conditions

As ships traverse the sea, they carry diverse goods, including hazardous or dangerous cargo, vital for economies worldwide. However, the very essence of the sea, characterized by its capricious and often tumultuous weather patterns, poses an imminent threat to the safe passage of such vessels. Avoiding risky weather conditions becomes paramount when navigating ships carrying hazardous cargo.

The formidable challenge of ensuring the safe voyage of ships loaded with dangerous cargo is inextricably linked to the understanding and anticipation of meteorological phenomena. Hazardous weather conditions, ranging from severe storms and cyclones to fog, ice, and rogue waves, can jeopardize both human lives and the delicate equilibrium of marine ecosystems. The stakes are higher when the cargo is volatile, toxic, or flammable, demanding heightened vigilance and preparedness.

In the face of these challenges, modern maritime technology has assumed a pivotal role. Cutting-edge meteorological data collection, advanced weather forecasting models, and communication systems enable ship captains and maritime authorities to make informed decisions safeguarding lives, cargoes, and the marine environment. These tools provide valuable insights into potential weather hazards, offering the opportunity to reroute, delay departure, or take other preventative measures.

While technological advancements offer a lifeline in the pursuit of safe passage, avoiding dangerous weather conditions for ships carrying hazardous cargo is multifaceted. It necessitates harmonising real-time meteorological information, navigational expertise, crew training, regulatory compliance, and stakeholder cooperation. Additionally, the ethical and legal dimensions surrounding the duty of care for human life, environmental protection, and adherence to international maritime guidelines further underscore the complexity of this challenge.

The goal is to avoid dangerous weather conditions for ships carrying hazardous cargo onboard. Examining the synergistic interplay of meteorology, technology, regulations, and human decision-making aims to enable the sustainable and secure movement of hazardous cargoes across the south Adriatic sea, where preserving life, environment, and commerce converge in a delicate balancing act.

3.2 Marine protected areas

3.2.1 Italy - Marine protected areas

MPAs are protected areas of marine environment (seas, oceans, estuaries, or Great Lakes) that are managed for conservation purposes. Authorities can declare an MPA for a variety of reasons, so the specific goals of each needs to be accessed to guide monitoring and research activities. Likewise, the restrictions can vary from seasonal closures of spawning sites to areas permanently closed to fishing and other resource activities, and may include marine parks that allow for different activities [2]. Marine protected areas are a globally recognized tool for managing and enhancing marine ecosystems [3].

In the last years, the European Union (EU) has made significant progress towards globally agreed targets regarding marine protected areas, with the aim of maintain the health of its seas:

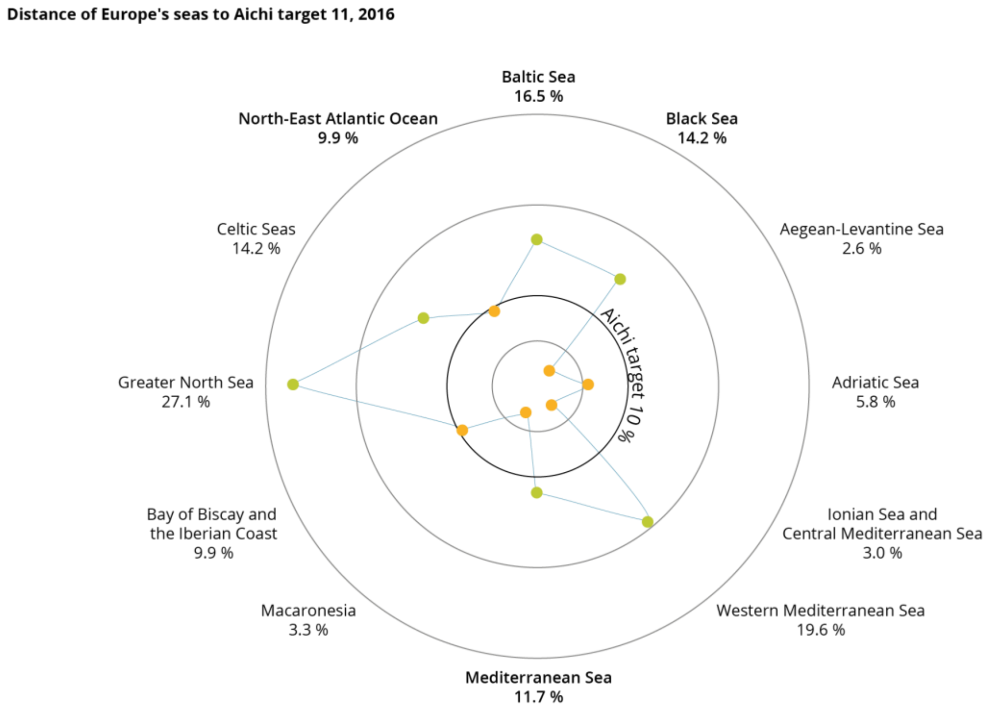


Figure 1 – Aichi targets for EU's seas and the distance to reaching them [3]

As can be seen in Figure 1, by 2016 20.8% of the surface of EU's seas had been classified as MPAs. Of particular interest to the CRISIS project, the Adriatic Sea is below the European average, with only 5.8% (or 120.069km^2) of its surface dedicated to MPAs. Moreover, many of the existing MPAs may be too small to fully deliver ecosystem services, with more than 50% measuring less than 30km^2; in the Adriatic Sea, almost 70% of MPAs have less than 5km^2 [3].

As for its distribution, MPA coverage is six times higher in coastal waters than in offshore waters across EU's regional seas - and this reality is reflected in the MPAs that fall within the Italian area of interest of this project, as can be seen in the map below:

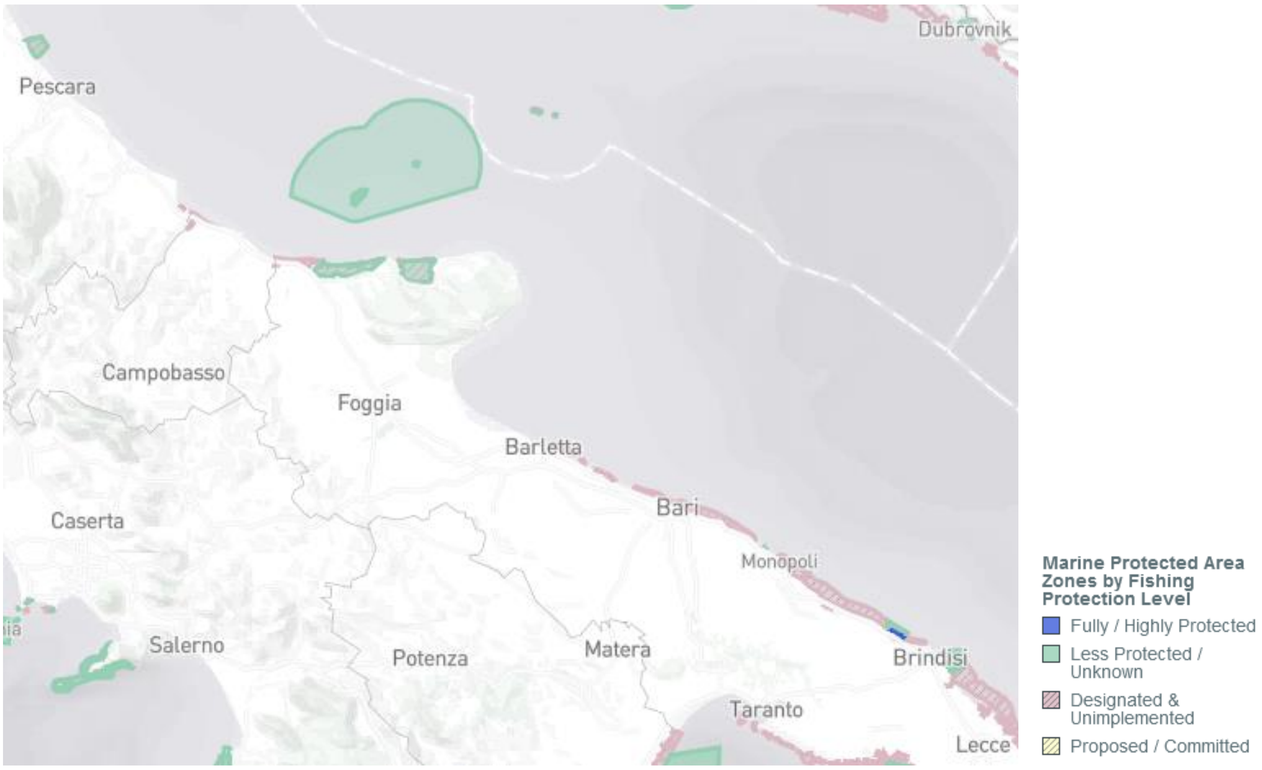


Figure 2 – MPAs in the Italian area of interest of the project CRISIS (image from [4])

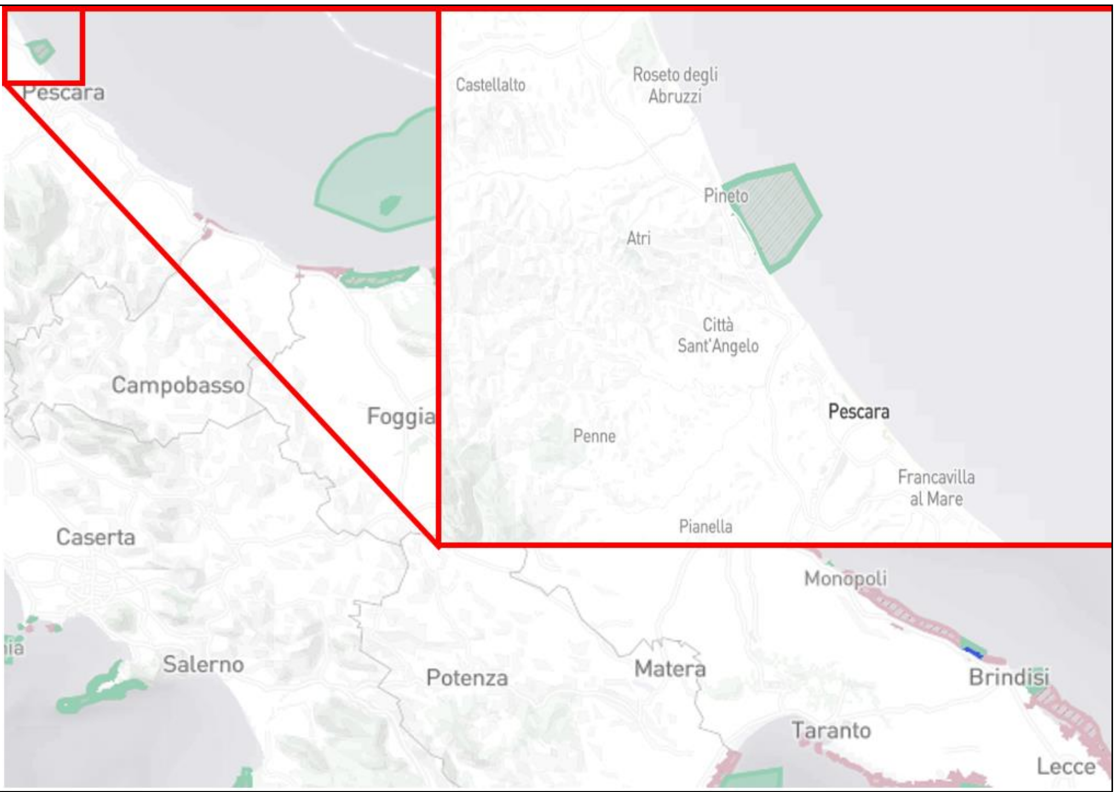
The marine protected areas can be divided in four types:

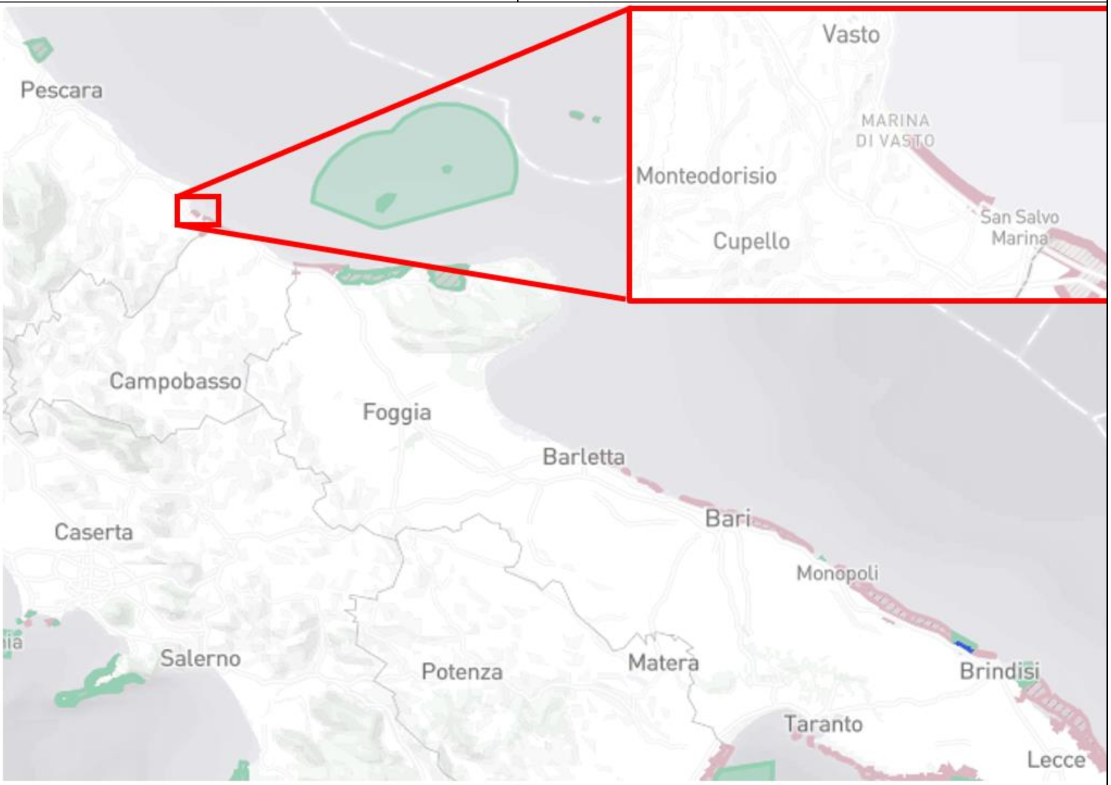
- Fully/Highly Protected: areas that prohibit or strictly restrict extractive activities, minimizing impact to the extent possible;
- Less Protected/Unknown: areas that afford some protection but allow moderate to extensive extraction and associated impacts;
- Designated & Unimplemented: an MPA is specifically codified or dedicated through legally recognized means or authoritative rule. The MPA now exists "on paper" and in law or other formal process;
- Proposed/Committed: the intent to create an MPA is made public, for example through a submission to the Convention on Biological Diversity or other instrument, conference announcement, official press release, or other official declaration.

As can be seen in Figure 2, the area of interest of this project has a few MPAs. Next pages are dedicated to describing the MPAs that fall within the Italian area of interest of the CRISIS project. They are described in order, from north to south. The maps were extrapolated from [4].

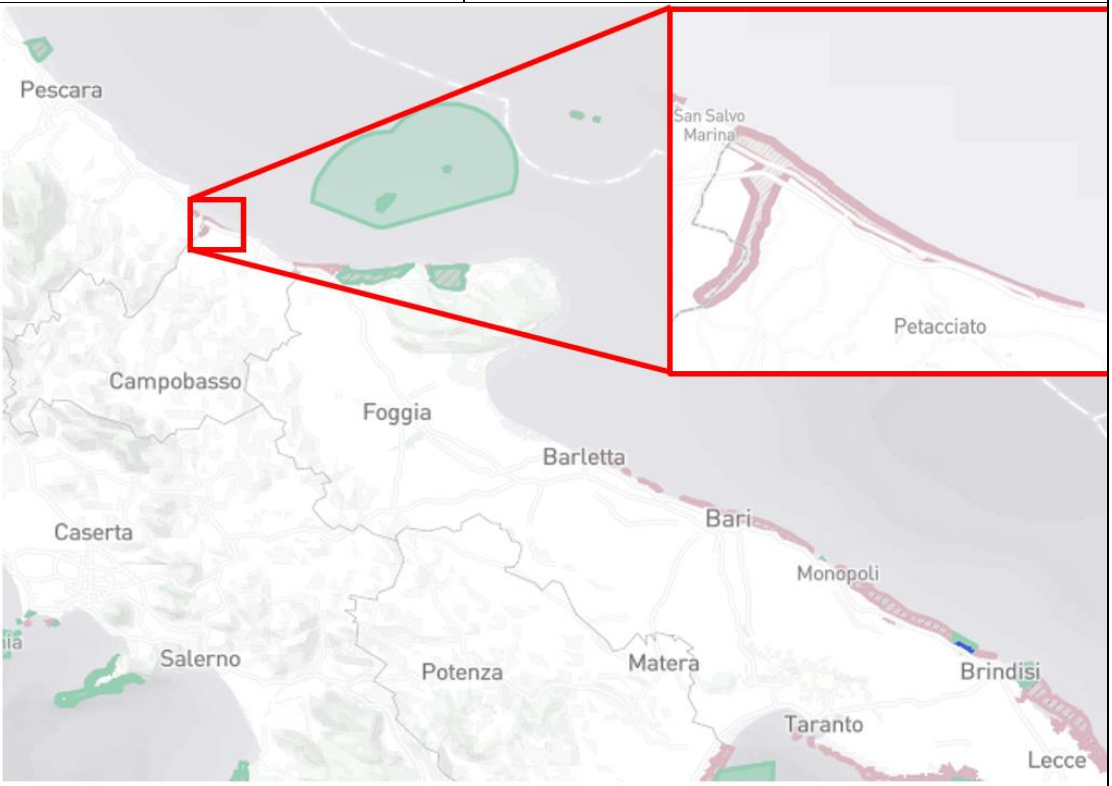
Name	Torre del Cerrano (IT7120215)[6]
Marine area (km^2): 34,1	Total area (km^2): 34,2

[6] Official website: https://www.torredelcerrano.it/

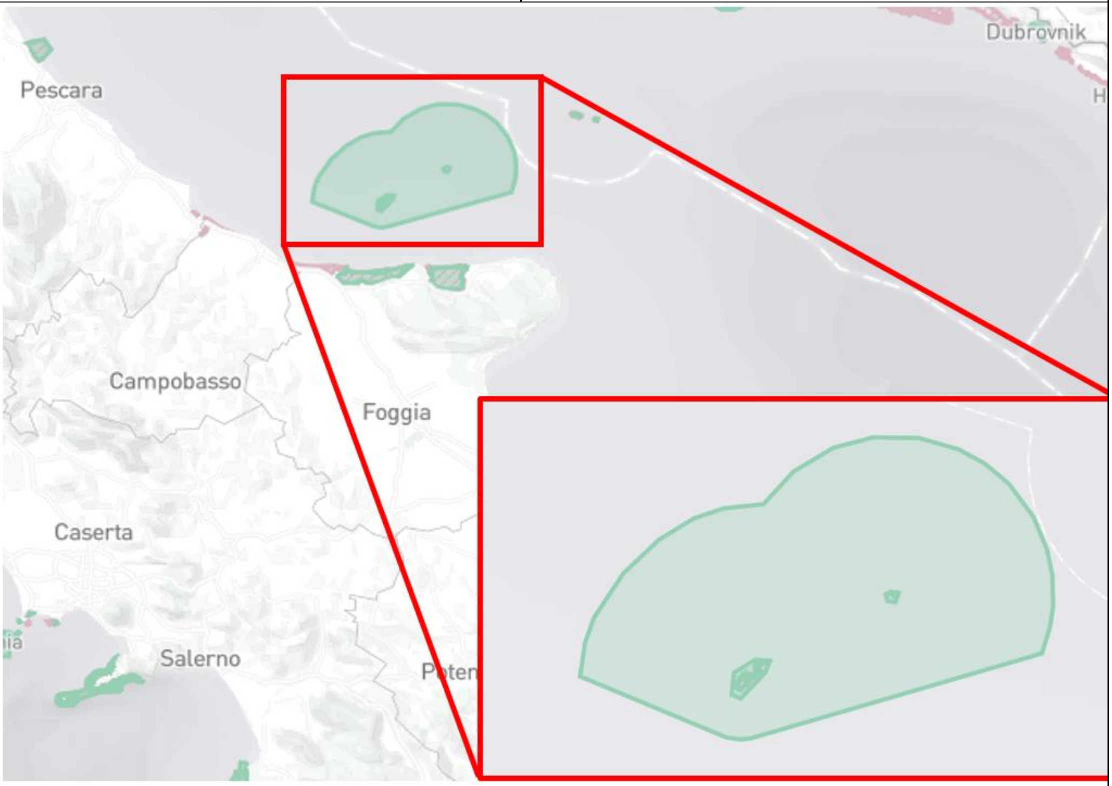
Map	
Description	The MPA was officially stablished in 2010. It is a province of Teramo, located between the municipalities of Silvi and Pineto. This area had an old roman port (Porto di Atri), that was destroyed by the Republic of Venice. Later, Carlo V constructed a watchtower, as a safety measure against Saracen invasions, and this tower has been a symbol in the region ever since. The delimitated area protects the rare dune habitat, as well as the archeological remains of the roman port. This MPA is divided in three zones: • Zone A: regards the sea in front of the tower and it's the zone with most restrictions of the MPA; • Zone B: protects the beach strip up to 2km from the coastal line; • Zone C: it is the biggest zone, in the form of a trapezoid with up to 3 nautical miles from the coast. In 2012, the EU recognized the MPA Torre del Cerrano as a Site of Community Interest in the Natura 2000 Network.

<table>
<tr><td>Name</td><td colspan="2">Marina di Vasto (IT7140109)[7]</td></tr>
<tr><td colspan="2">Marine area (km^2): 0,241</td><td>Total area (km^2): 0,566</td></tr>
<tr><td>Map</td><td colspan="2">
</td></tr>
<tr><td>Description</td><td colspan="2">Located in the Municipality of Vasto, this MPA was stablished in 2007 (EUAP1207, LR n°5 20/03/07). It is also part of Natura 2000 Network.
The preservation of the “fratino” (Charadrius alexandrinus), a protected species of bird, is of particular interest of this MPA. In fact, one of its restrictions is the ingress of dogs in the beach during the nesting period of this species.
As for the marine area, this MPA covers only 5 meters from the coastal line. [5]</td></tr>
</table>

[7] https://www.parks.it/riserva.marina.vasto/par.php

Name	Foce Trigno – Marina di Petacciato (IT7228221)[8]	
Marine area (km²): 0,429		Total area (km²): 7,47
Map		
Description	This MPA covers the Trigno river mouth and adjacent coastal areas, including the Petacciato Marine. The area is rich in bird species.	

[8] https://www.parks.it/dbparks/dettaglio.php?codiceAP=S1610

Name	Isole Tremiti[9]	
Marine area (km²): 1.932		Total area (km²): 1.935
Map		
Description	The MPA covers an archipelago known in ancient times as "*Isole Diomdee*" (Tremiti Islands). To protect the uniquely beautiful landscape, in 1989 the Natural Reserve was constituted, and in 1991 the Gargano National Park was established. Studies individuated 17 different marine habitats within the MPA:	

[9] https://www.parcogargano.it/amp-isole-tremiti/

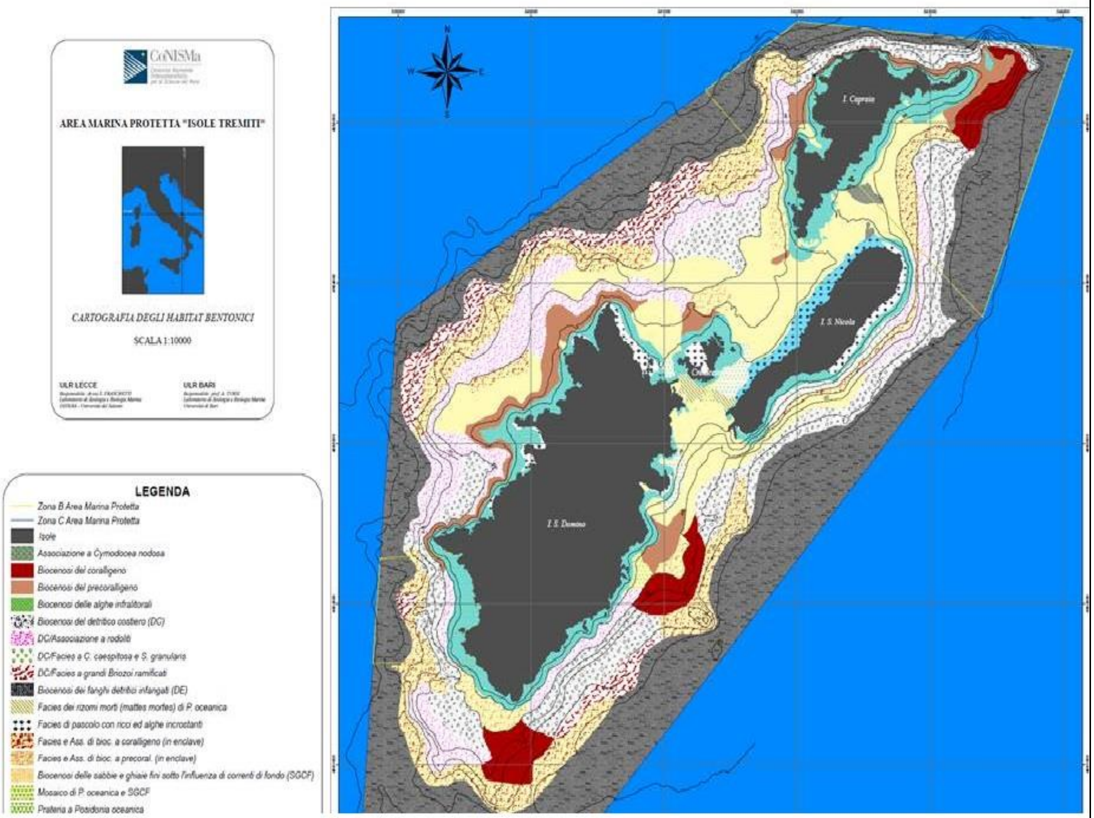
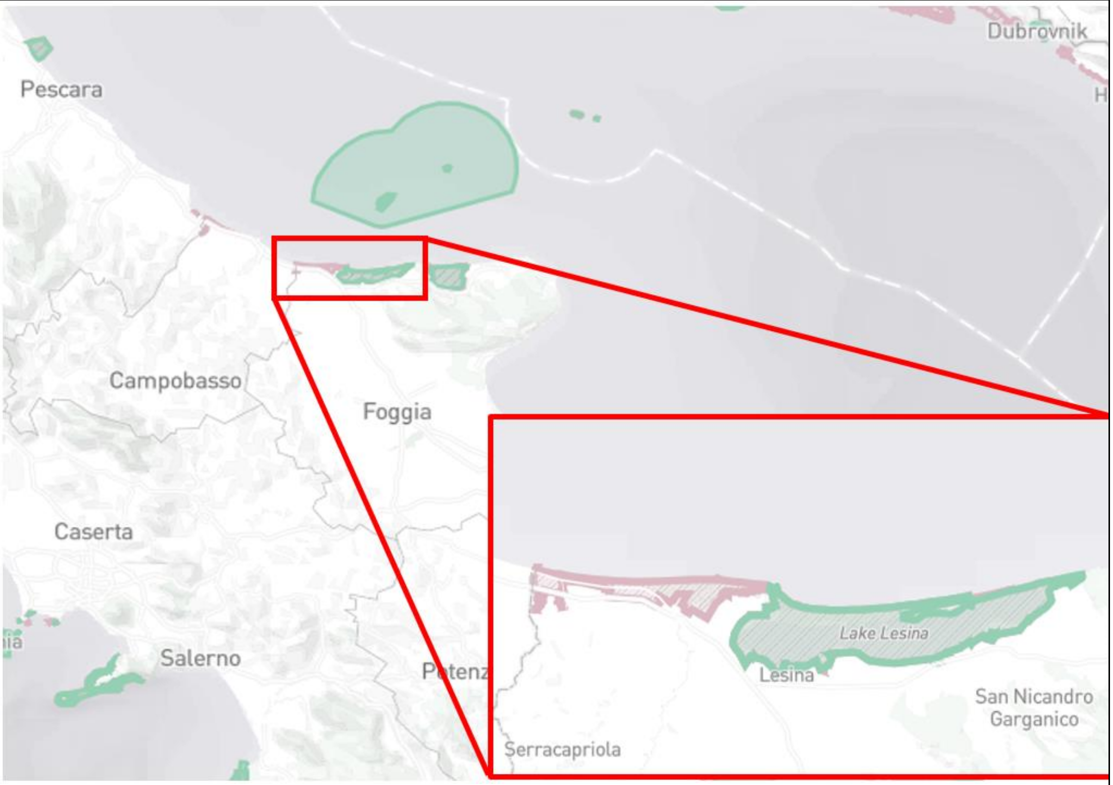


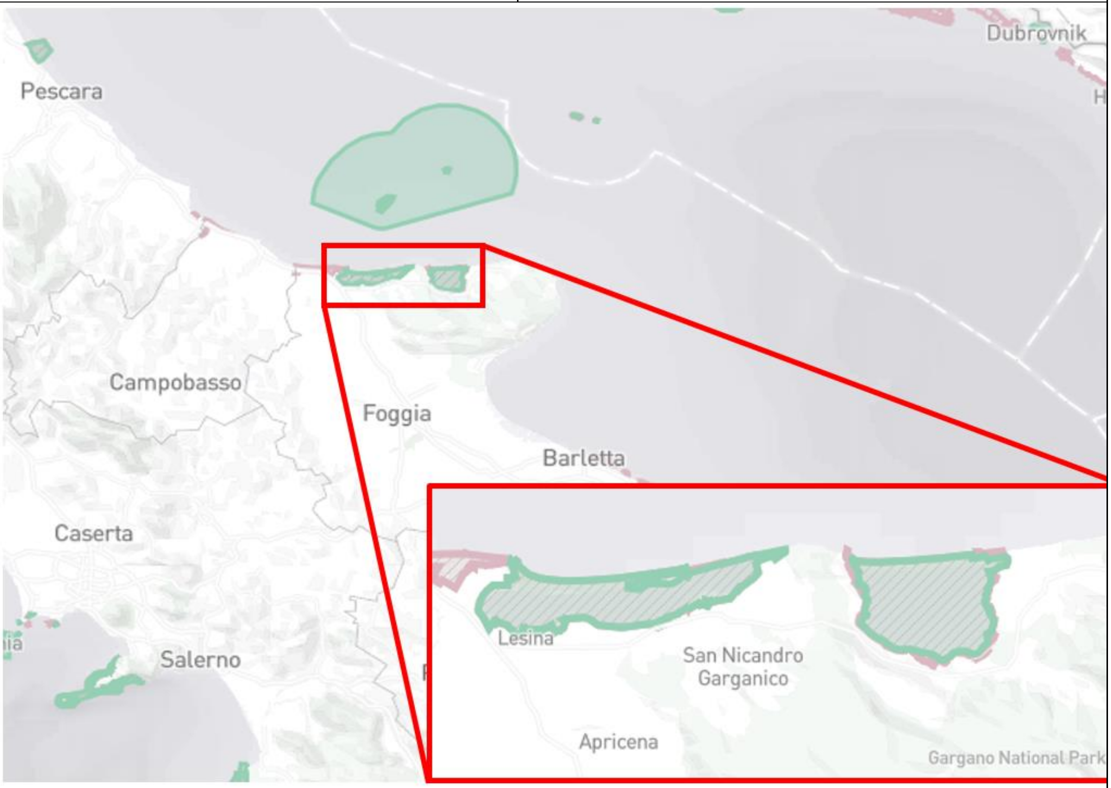
Figure 3 – Cartography of the habitats of the Isole Tremiti MPA [6]

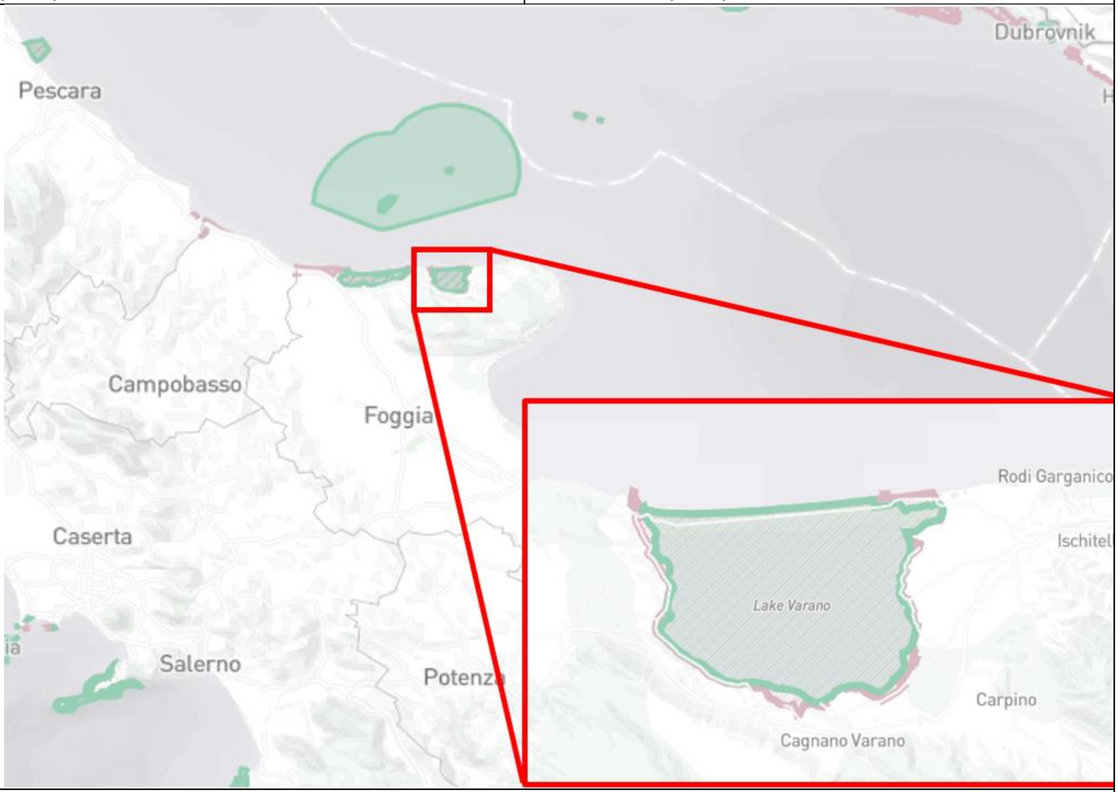
The MPA is divided in three zones (A, B and C), with different levels of restrictions [7]:

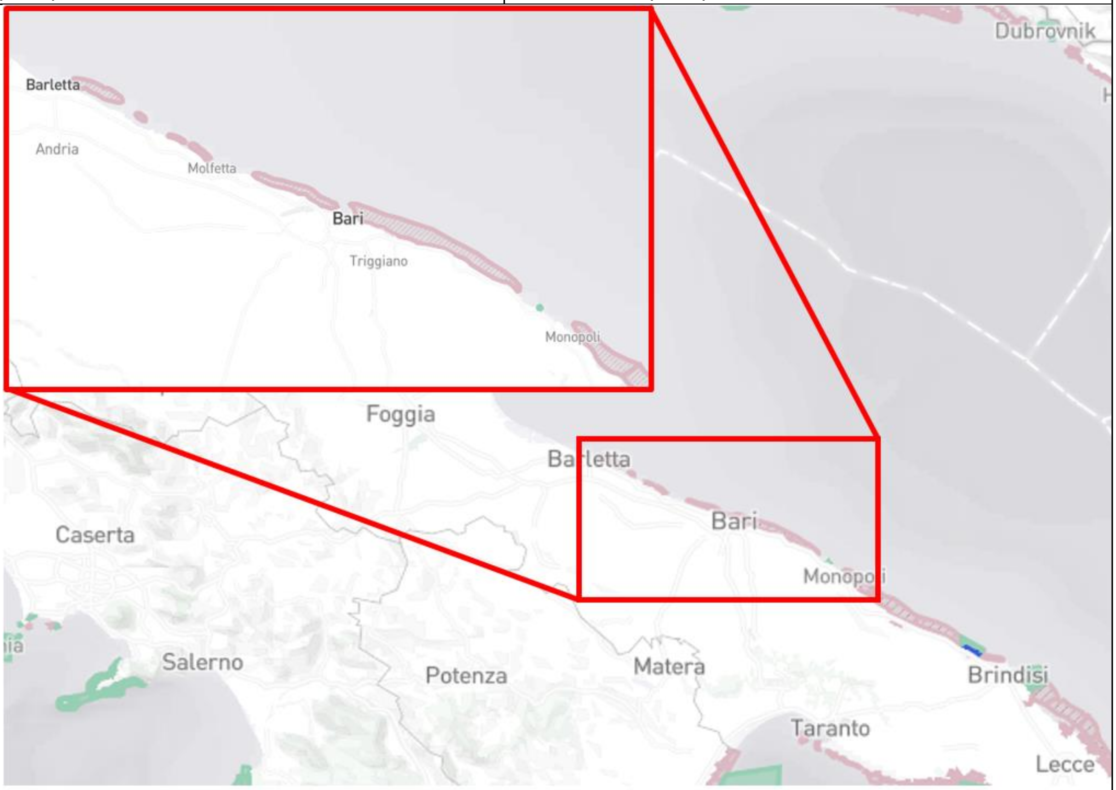
Activity	Zone A	Zone B	Zone C
Scientific research	With authorization	With authorization	With authorization
Navigation	No	With authorization	Yes
Swimming	No	Yes	Yes
Anchoring	No	No	Yes
Diving	No	With authorization	Yes
Small-scale fishing	No	With authorization	With authorization
Leisure fishing	No	No	Yes
Underwater fishing	No	No	No

<table>
<tr><td>Name</td><td colspan="2">Duna e Lago di Lesina – Foce del Fortore[10] (ZSC IT 9110015)</td></tr>
<tr><td colspan="2">Marine area (km²): 2,3</td><td>Total area (km²): 98,3</td></tr>
<tr><td>Map</td><td colspan="2">
</td></tr>
<tr><td>Description</td><td colspan="2">The MPA was established in 1981 as an area for animal repopulation– it is an important stop in the migration route of a number of aquatic birds between Europe and Africa (more than 200 species), many of which also use the area for reproduction. The lake is part of the Gargano National Park, and access is allowed only for study and scientific research purposes and require written authorization by the competent authorities. Besides the aquatic birds, the area is visited by a rich array of animals, including the Caretta Caretta turtle, that visits the region to lay eggs. [8]
The MPA is part of Natura 2000 Network.
The Lesina lake connects with the sea in three different points.</td></tr>
</table>

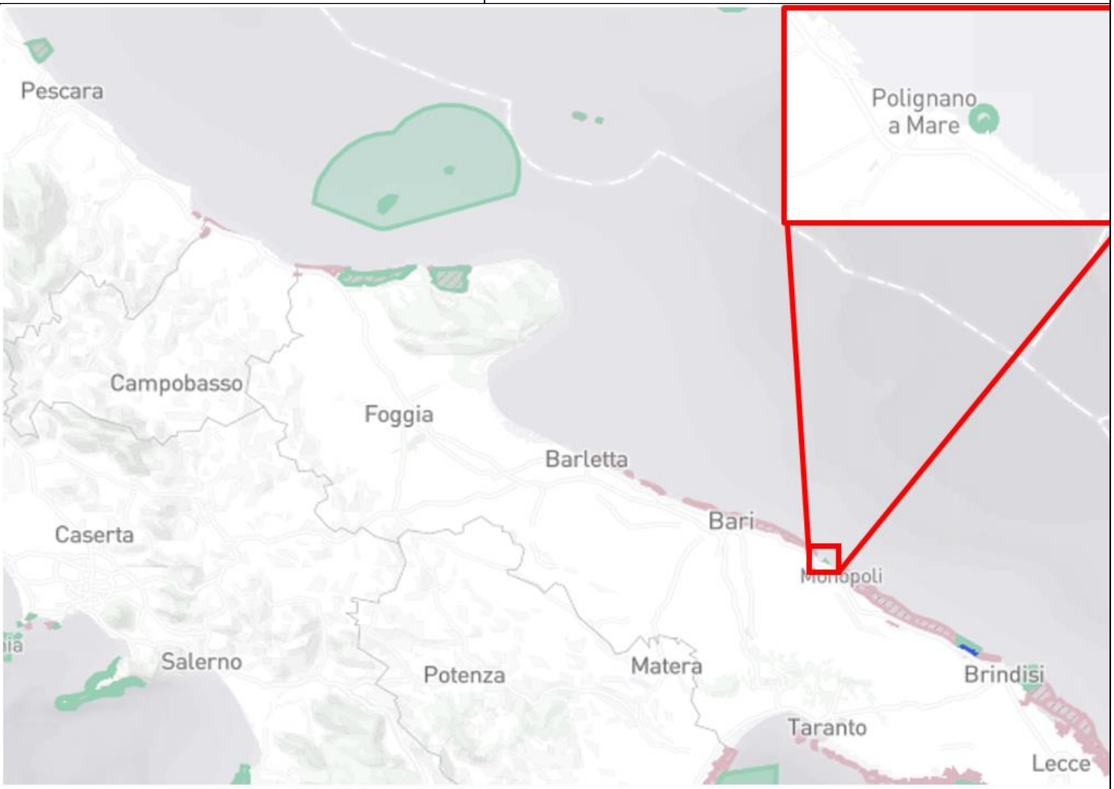
[10] https://www.parks.it/parco.nazionale.gargano/par.php

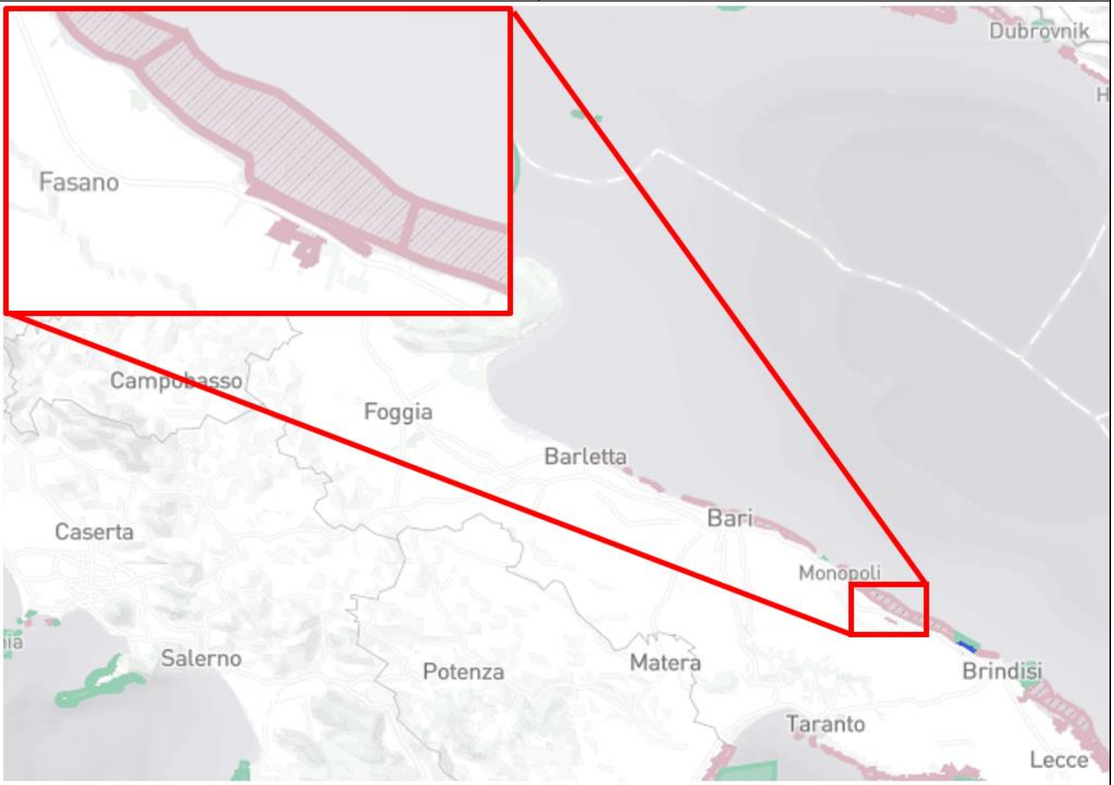
Name	Laghi di Lesina e Varano (ZPS IT9110037)	
Marine area (km^2): 1,7		Total area (km^2): 152
Map		
Description	A good portion of this conservation area coincides with the "Duna e Lago di Lesina – Foce del Fortore" MPA, with the added area of Varano lake. The MPA is part of Natura 2000 Network.	

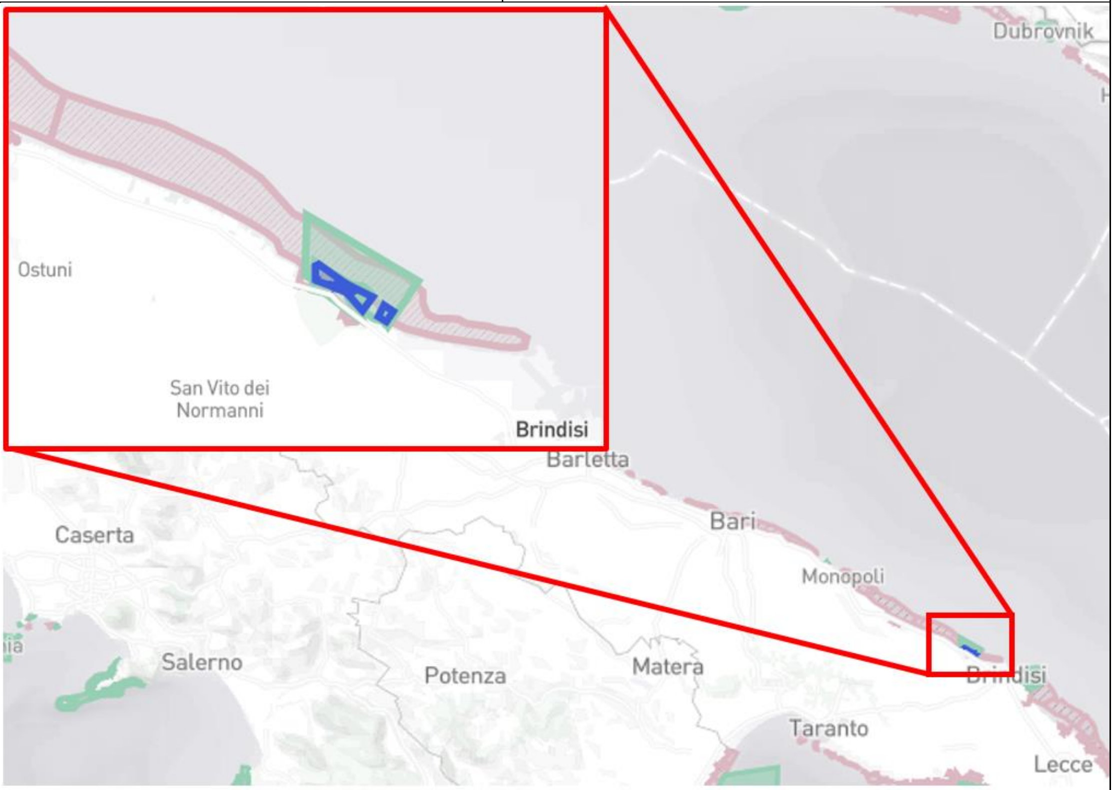
Name	Isola e Lago di Varano (ZSC IT9110001)	
Marine area (km^2): 0,82		Total area (km^2): 81,5
Map		
Description	The island is a strip of land that separates lake Varano from the Adriatic Sea. In 1997 it was established as a Strict Nature Reserve, and its area falls within the Gargano National Park. The MPA has a rich population of aquatic bird species.	

Name	Posidonieto San Vito – Barletta[11] (IT9120009)
Marine area (km^2): 125	Total area (km^2): 125
Map	
Description	The MPA falls within the municipalities of Bari, Barletta, Bisceglie, Moldetta, Monopoli and Trani, and is 100% composed of marine area. There is no actual management plan – at least not present in the Natura 2000 database, of which the MPA is part of. Of particular environmental relevance is the coral biocenosis in the zone, that develops between 18 and 27 meters in the bathymetric range. [9]

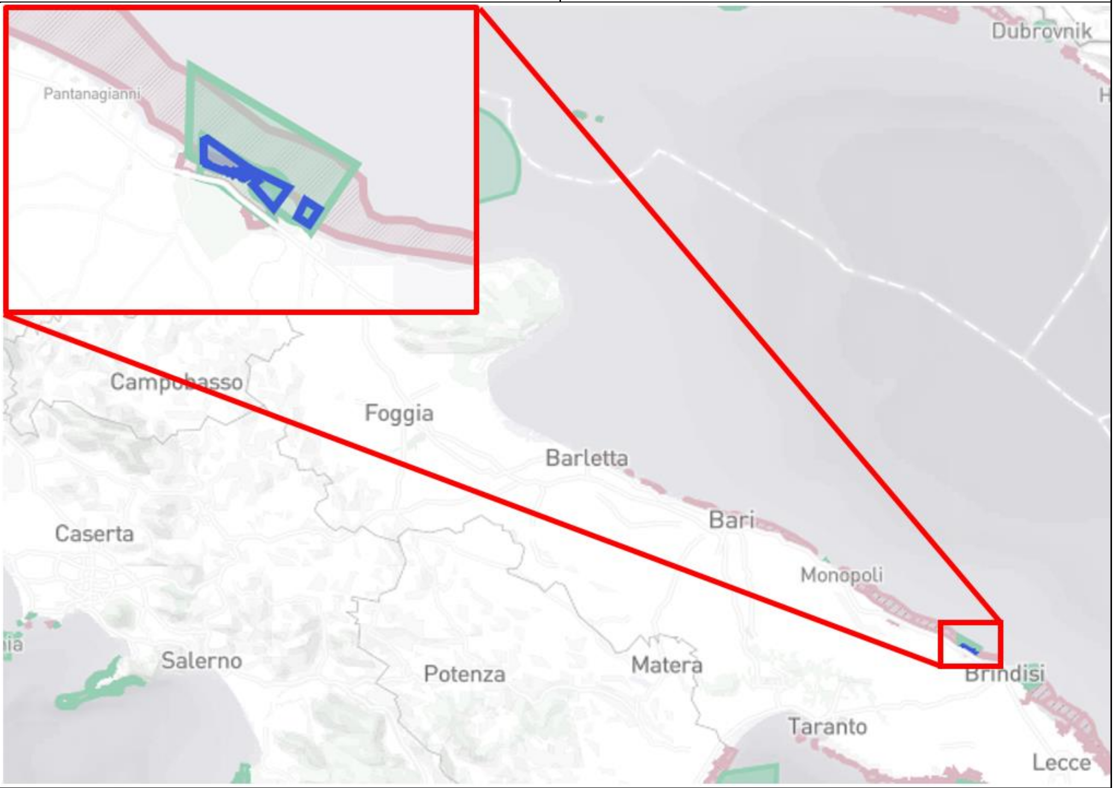
[11] https://www.parks.it/dbparks/dettaglio.php?codiceAP=S1943

<table>
<tr><td>Name</td><td colspan="2">Scoglio dell’Eremita (IT9120012)</td></tr>
<tr><td colspan="2">Marine area (km²): 0,142</td><td>Total area (km²): 0,178</td></tr>
<tr><td>Map</td><td colspan="2">
</td></tr>
<tr><td>Description</td><td colspan="2">It is a Special Conservation Zone (ZPS, Zona di Protezione Speciale), because this reef is home to a rare species of bird, the Larus Audounii.</td></tr>
</table>

Name	Litorale Brindisino	
Marine area (km^2): 68,4		Total area (km^2): 72,5
Map		
Description	This MPA is a Site of Community Importance (SIC, *Sito di Importanza Comunitaria*), in the Natura 2000 Network. This zone is characterized by the presence of rare or endangered migratory birds.	

<table>
<tr><td>Name</td><td colspan="2">Torre Guaceto e Macchia S. Giovanni (IT9140005)[12]</td></tr>
<tr><td colspan="2">Marine area (km²): 76,6</td><td>Total area (km²): 79,7</td></tr>
<tr><td>Map</td><td colspan="2">
</td></tr>
<tr><td>Description</td><td colspan="2">It is a Nature 2000 Network site, due to its archeological and landscape importance. Its management plan was approved in Regional Decree n.89 of 19.05.2010. 95% of its area falls in the sea, in the Municipalities of Carovigno and Brindisi.</td></tr>
</table>

[12] https://natura2000.eea.europa.eu/Natura2000/SDF.aspx?site=IT9140005

Name	Torre Guaceto[13], [14]	
Marine area (km^2): 21,6		Total area (km^2): 21,8
Map		
Description	This MPA is a Specially Protected Area of Mediterranean Importance (ASPIM, *Area Specialmente Protetta di Importanza Mediterranea*). The area falls within the ZSC IT9140005 "*Torre Guaceto e Macchia S. Giovanni*" and is regulated by Decree n.42 in *Gazzetta Ufficiale* of 20.02.2009., which foresees the protections of a marine protected area, divided in three :	

[1313] https://www.mase.gov.it/pagina/area-marina-protetta-torre-guaceto

[14] https://www.riservaditorreguaceto.it/index.php/it/

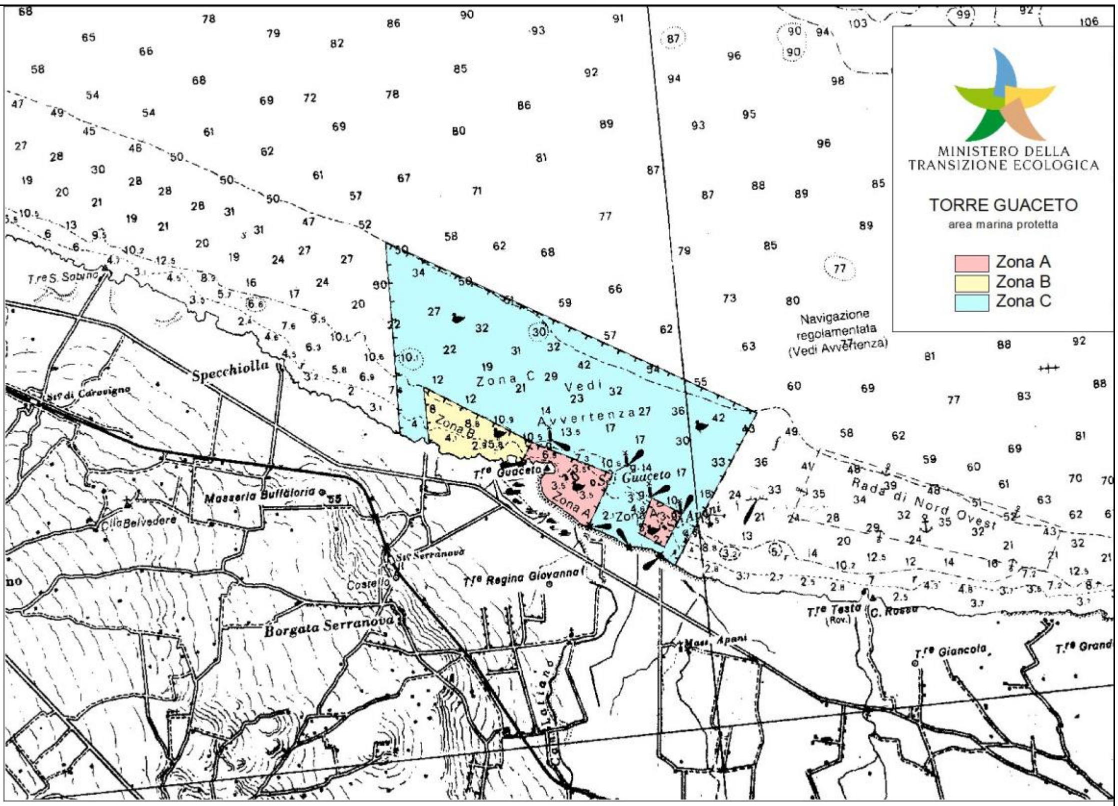
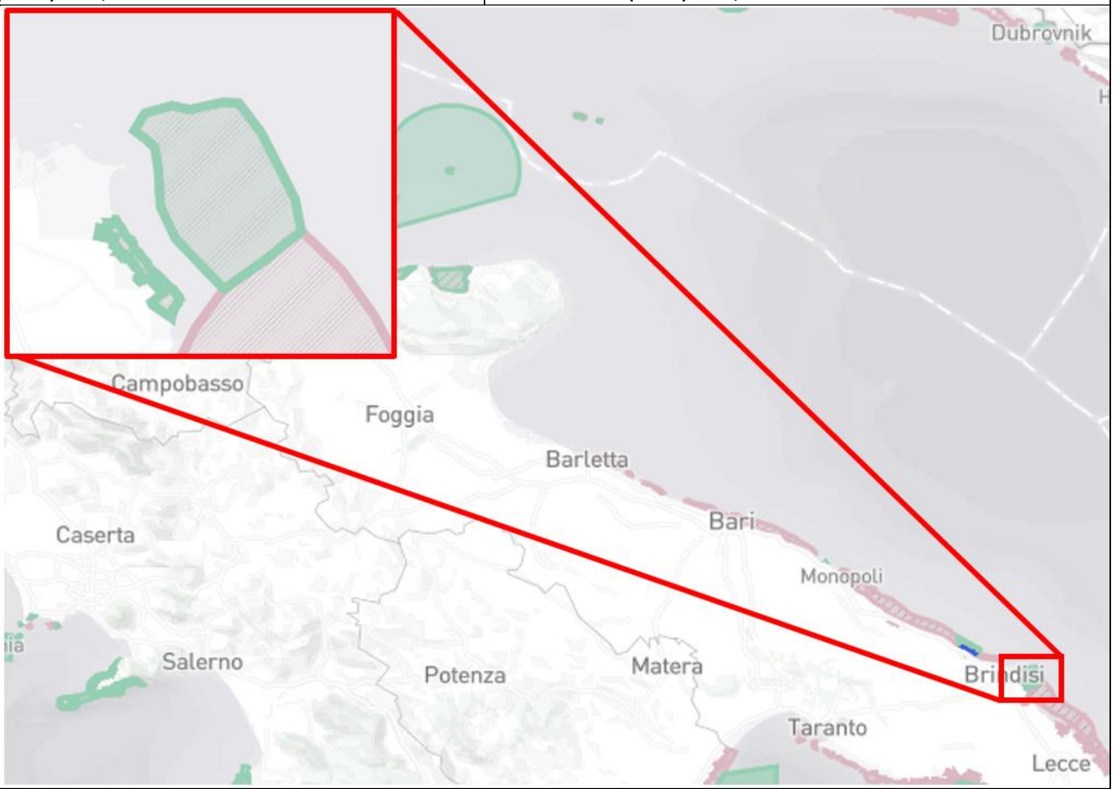


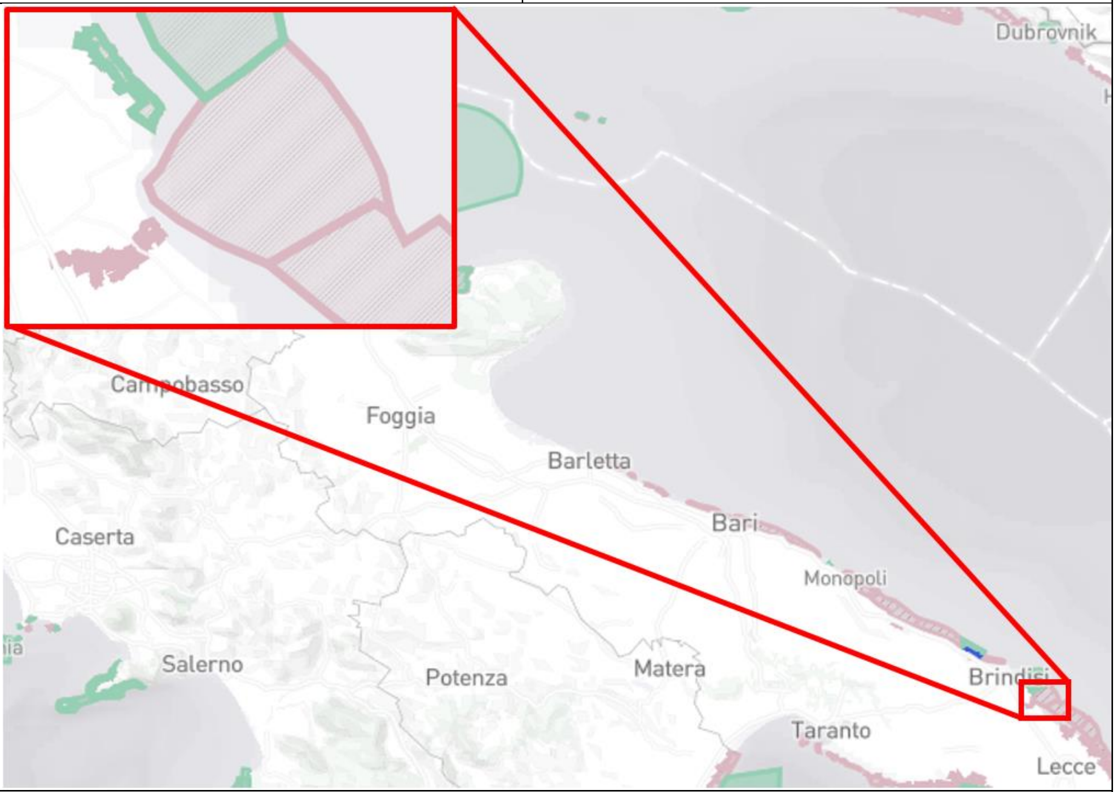
Figure 4 – Zones of the "Torre Guaceto" MPA (Ministero dell'Ambiente e della Sicurezza Energetica, 1991)

The zones have the following restrictions [10]:

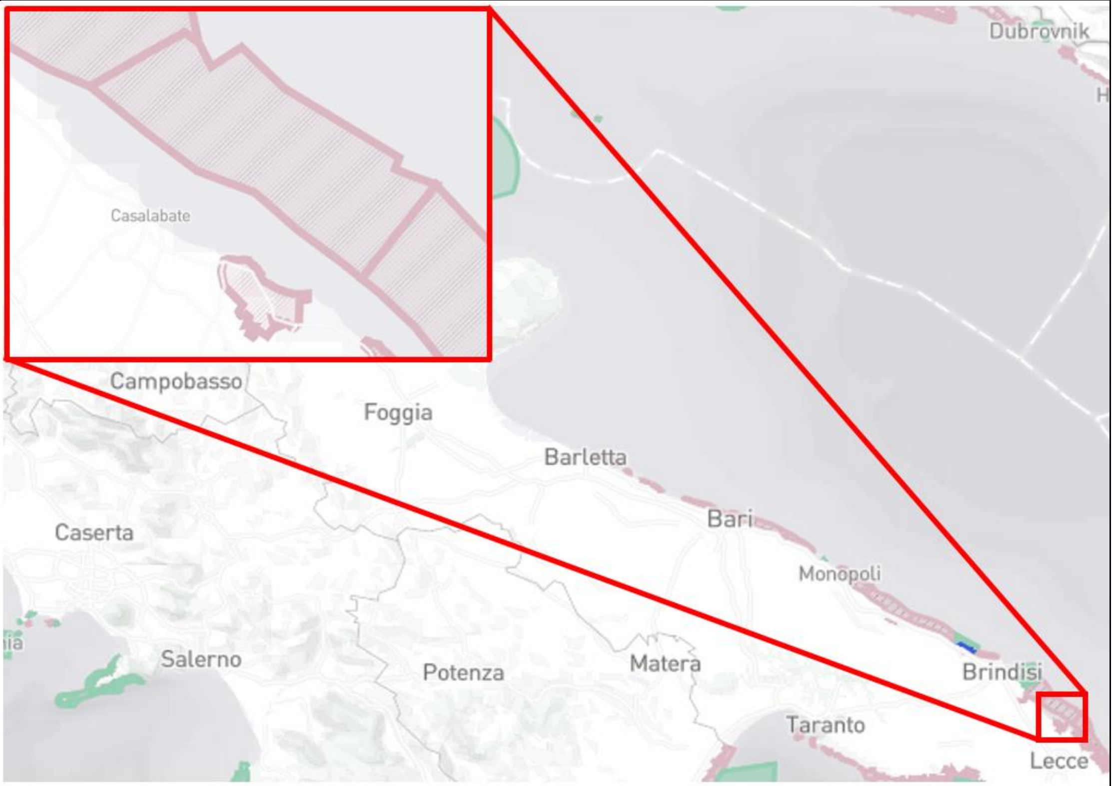
Activity	Zone A	Zone B	Zone C
Scientific research	With authorization	With authorization	With authorization
Navigation	No	Without engine propulsion	Without engine propulsion
Swimming	No	Yes, during daytime	Yes, during daytime
Anchoring	No	No	No
Diving	Only scuba diving with authorization	With authorization	With authorization
Small-scale fishing	No	No	With authorization
Leisure fishing	No	No	With authorization
Underwater fishing	No	No	No

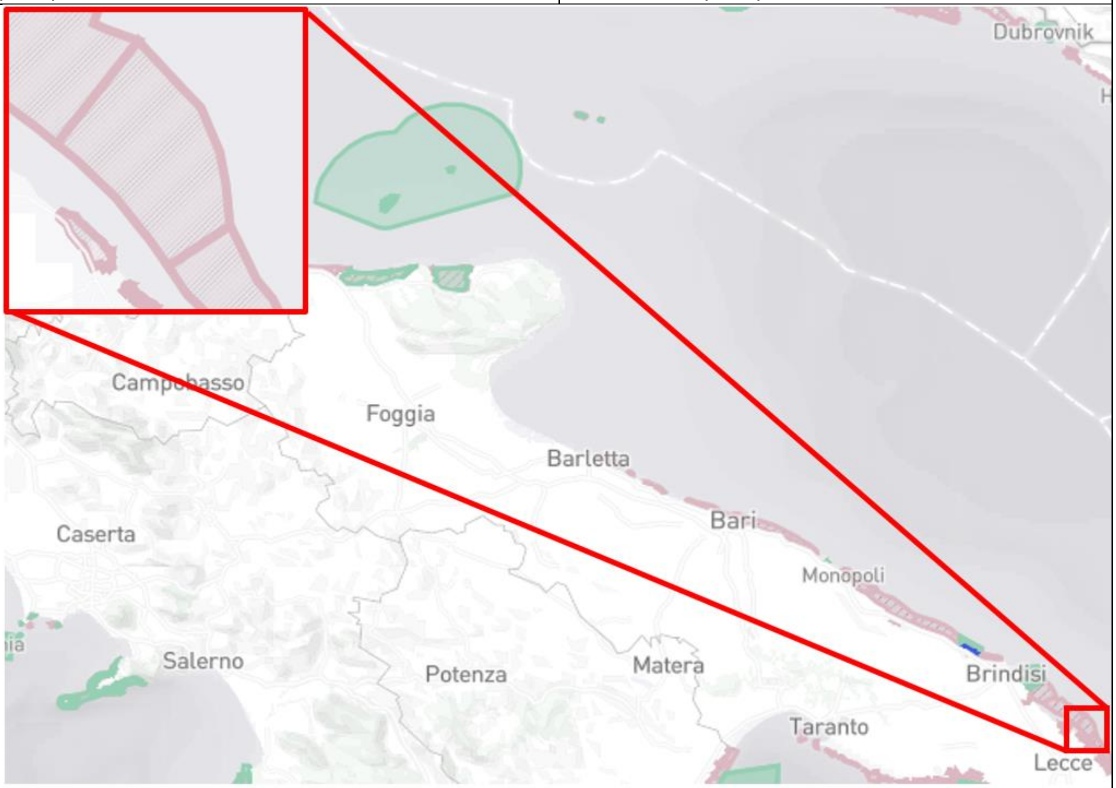
This MPA is also a Specially Protected Area of Mediterranean Importance within Italy, according to the Barcelona Convention.

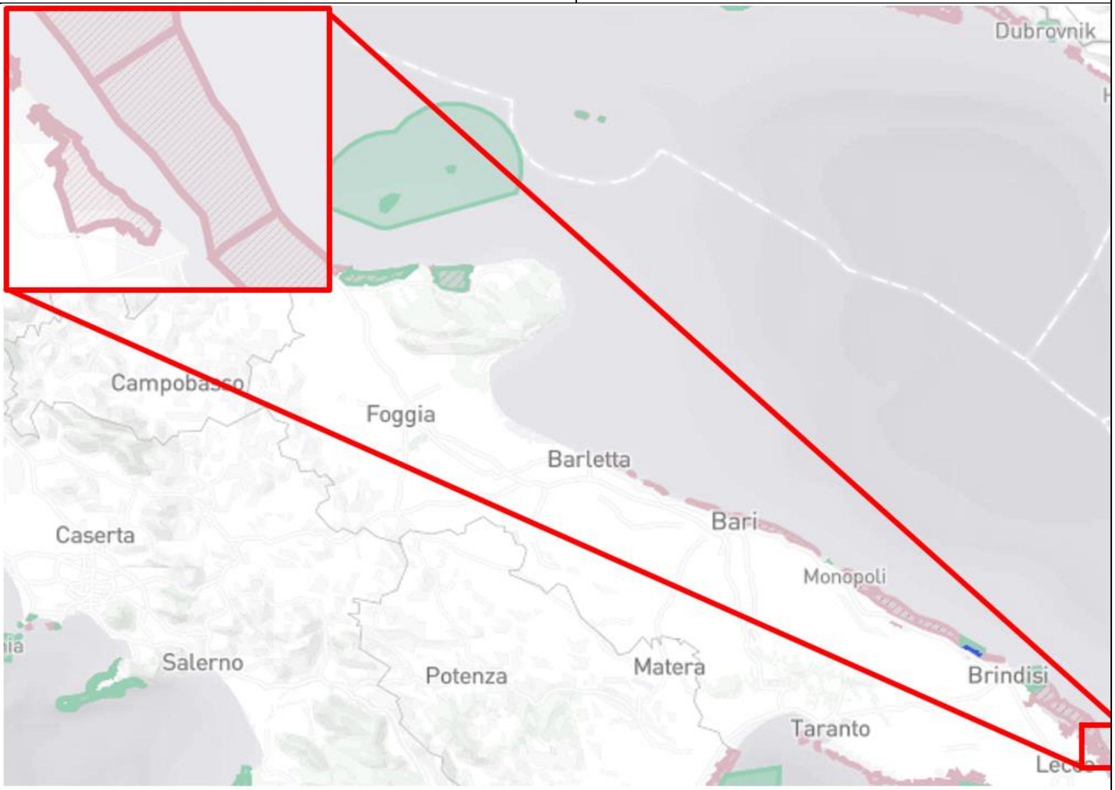
Name	Stagni e Saline di Punta della Contessa (IT9140003)	
Marine area (km^2): 26,8		Total area (km^2): 28,6
Map		
Description	This area has two Priority Habitats (as defined by Directive 92/43/CEE): Lagoons and Salt Steppes. It is also the habitat of rare migratory birds. The MPA, which falls within the Brindisi Municipality, was approved in 2002 with a regional decree (n.164 of 30.12.2002). It has two zones: • Zone 1: central zone • Zone 2: protection band In the MPA it is prohibited to: open new quarries, hunt, disturb the fauna, collect or damage the flora (with the exception of approved research studies), collect minerals (with the exception of approved research studies), introduce foreign species, disturb the ecological equilibrium, transit with motorized vehicles outside the roads (with the exception of vehicles for farming and forestry activities), build new roads or amplify existing ones, one dump sites. Farming and forestry are allowed. [11]	

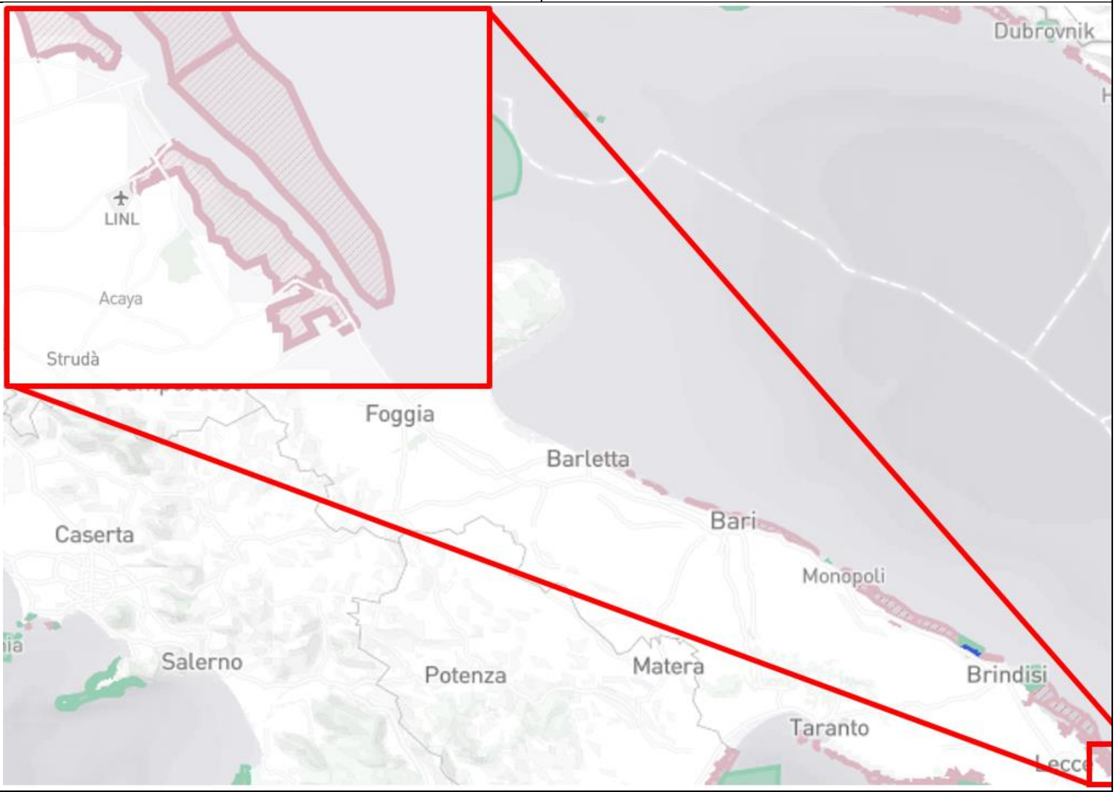
Name	Bosco Tramazzone (IT9140001)[15]	
Marine area (km²): 42,8		Total area (km²): 44,0
Map		
Description	The area is home to a rare indigenous hygrophilous plant, and is also in the route for migratory birds.	

[15] https://www.parks.it/dbparks/Edettaglio.php?codiceAP=S1949

Name	Rauccio (IT9150006)	
Marine area (km^2): 60		Total area (km^2): 65,8
Map		
Description	The MPA was registered in 1995 with Decree *D.M. Ambiente del 3/4/2000 G.U.95 del 22/04/2000*, and falls within the Municipality of Lecce. In the MPA it is prohibited to: open new passages in the dunes, build new structures or amplify existing ones, modify the landscape, transit or park motorized vehicles.	

Name	Aquatina di Frigole (IT9150003)	
Marine area (km²): 30,7		Total area (km²): 31,6
Map		
Description	The area consists of dunes vulnerable to erosion. The site is managed by the Salento University.	

Name	Torre Veneri (IT9150025)
Marine area (km^2): 13,6	Total area (km^2): 17,4
Map	
Description	The MPA approved management plan allows free access to the area, but restricts transit with motorized vehicles to farming, forestry or authorized activities. It also prohibits fire or camping outside designated areas. Lights or loud noises that may disturb the fauna are prohibited. Other activities that are prohibited include: littering, hunting outside the allowed season, disturb, capture or harm protected species, build wind farms, introduce foreign species, spray herbicidal substances, dry out the humid zones, disturb the natural landscape, touristic access the beaches from May to September (as it the nesting period for the Caretta caretta turtle), collect plants (except for authorized research), clean up natural areas or expand farming, , open new dump sites, build new roads, open new quarries or expand existing ones, ecc. For the full list of allowed or prohibited activities consult the MPA’s Management Plan [12].

Name	Le Cesine (IT9150032)[16]	
Marine area (km^2): 14,3		Total area (km^2): 21,5
Map		
Description	The MPA is a wetland situated in the Municipality of Vernole, home to an endangered species of plant (*periploca maggiore*). The natural reserve was established in 1980 by the Ministry of Agricolture and Forestry. Besides being a Site of Community Interest (SIC IT 9150032), it is a Special Protection Zone (ZPS IT 9150014).	

3.2.2 Albania - Marine protected areas

Montenegro and Albania are two neighbouring countries on the East Adriatic coast that share many valuable natural resources especially the ones related to marine areas, landscapes, and natural biodiversity heritage. Therefore, the initiatives to protect particular places of great importance, national interest as well as the uniqueness of natural beauties, have arisen in order to set up the rules for marine areas management and legislation that determines the allowed and forbidden activities in these areas, marine protected areas management plans, sustainable development and navigation in these areas, implementation of research, development, and investigation project activities.

[16] http://www.riservalecesine.it/

Albania has a coastline 427 km long: 273 km of coast in the West facing the Adriatic Sea and 154 km of coast in the South West on the Ionian Sea. Internal waters represent 735 km2 and the territorial waters (extending from the internal waters to 12 nautical miles offshore) represent 5,322 km2 .[17]

The Regional Project for the Development of a Mediterranean Marine and Coastal Protected Areas (MPAs) Network through the boosting of MPA Creation and Management "MedMPAnet Project" (http://medmpanet.rac-spa.org) was a five-year programme (2010-2015) executed by the Regional Activity Centre Specially Protected Areas (RAC/SPA – UNEP/ MAP; www.rac-spa.org). The MedMPAnet Project mainly dealt with the processes leading to the creation of marine and coastal protected areas in several Mediterranean countries (Algeria, Albania, Croatia, Egypt, Lebanon, Libya, Montenegro, Morocco, Tunisia).

The MPA establishment process goes generally through the following steps[18]:

- Legal and Institutional framework assessment for conservation of coastal and marine biodiversity,
- ecological studies,
- socio-economic and fishery studies,
- management planning,
- elaboration of stakeholders' participation and engagement mechanisms,
- elaboration of sustainable financing mechanisms.

Particular attention was paid to the vulnerable/sensitive Mediterranean habitats and species of conservation interest which are listed in:

- EU Habitat Directive (92/43) with five annexes dealing with *Natural Habitat Types, Animal and Plant Species of Community Interest*, *Strictly protected species and species whose exploitation is regulated,*
- Barcelona Convention (1995) and its SPA/BD Protocol concerning Specially Protected Areas and Biological Diversity in the Mediterranean sea.

Proposed Marine and Coastal Protected Areas in Albania are[19]:

- The Bay of Porto-Palermo (Himarë),
- The area from Vjosa river mouth to Sazan and Karaburun (the entire Vlora Bay),
- The area from Cape Rodoni to Patoku lagoon,
- The coastal area from the Buna river mouth to Viluni lagoon.

The major legal acts governing the conservation of Protected Areas in Albania are:

[17] https://www.rac-spa.org/sites/default/files/doc_medmpanet/final_docs_albania/d.albania_and_mpas_en.pdf

[18] UNEP/MAP, RAC/SPA, „Montenegro and Marine Protected Areas - Legal and Institutional Framework Assessment for Conservation of Coastal and Marine Biodiversity and the Establishment of MPAS", IUCN, 2014.

[19] https://www.rac-spa.org/sites/default/files/doc_medmpanet/final_docs_albania/d.albania_and_mpas_en.pdf

- Law for "Protected Areas" (8906 of 06.06.2002) amended by the Law "On some supplements and changes in Law 8906 of 06.06.2002" (9868 / 04.02.2008),
- Law on "Biodiversity Protection" (9587 of 20.07.2006),
- Law on "Protection of the Marine Environment from Pollution and Damage" (8905 / 06.06.2002),
- Law on "Fishery and Aquaculture" (7908 / 05.03.1995), revised in 2012 and adopted as the Law on "Fishery" (64/2012 / 31.05.2012),
- Law on Environment Protection (Nr. 10 431 / 09.06.2011)
- Law for the Environmental Impact Assessment (Nr. 10 440 / 07.07.2011)[20].

3.2.3 Montenegro - Marine protected areas

Montenegro has 293 km of coastline along the Adriatic Sea and its maritime zone extends up to 12 nautical miles offshore covering an area of about 2,500 km², with a maximum depth of 1.233 m2 . The width of the continental shelf (up to 200 m depth) varies along the coast of Montenegro, extending to 9.5 nautical miles at the entrance of the Bay of Kotor, and 34 nautical miles at the River Bojana estuary.[21]

Considering the abovementioned directives for natural protected areas, Montenegro developed a list of 32 candidate Emerald Ecologic Network sites (also defined as Areas of Special Conservation Interest at the European level - ASCIs), covering a total area of 234,399 ha, out of which 12 are located in the coastal region or at sea: Skadar Lake; Velika Plaža with Solana Ulcinj; Buljarica; Tivatska solila; Šasko jezero; Bojana river, Knete, Ada Bojana; Kotor-Risan bay; Orjen; Pecin beach; Spas hill in Budva; Katič, Donkova and Velja seka islands; and Platamuni.

There are no specific laws or policies dealing solely with Marine Protected Areas in Montenegro. Instead, the main laws and strategic documents that apply for Protected Areas in general also apply for MPAs. The two major legal acts governing the proclamation and management of Protected Areas, including marine protected areas, in Montenegro are:

1 The Law on Nature Protection and

2 the Law on National Parks.

Coastal ecosystems are protected under the Law on Nature Protection, as follows[22]:

---

[20] https://www.rac-spa.org/sites/default/files/doc_medmpanet/final_docs_albania/d.albania_and_mpas_en.pdf

[21] https://www.racspa.org/sites/default/files/doc_medmpanet/final_docs_montenegro/y.en_adriatic_montenegro.pdf

[22] UNEP/MAP, RAC/SPA, „Montenegro and Marine Protected Areas - Legal and Institutional Framework Assessment for Conservation of Coastal and Marine Biodiversity and the Establishment of MPAS", IUCN, 2014.

- Article 21 (protection of the sea and seabed),
- Article 37 (definition of protected natural areas),
- Article 49 (categorization of protected natural areas),
- Article 54 (establishing protection zones in the protected nature areas),
- Article 45 (establishing the list of strictly protected and protected wild species of plants, animals and fungi).

The provisions of the Law regarding the management of protected areas (Article 62 and Article 65-67), are also relevant, especially in terms of establishing and managing protected areas on land and sea.

Three sites for proposed Marine Protected Areas were identified in the Special Purpose Spatial Plan for the Coastal Zone of Montenegro (2007):

1 Platamuni,
2 Katič islands and
3 Old Ulcinj island.

By the decision of the Government of Montenegro, based on the Law on Nature Protection (Official Gazette of Montenegro, No. 54/16), three protected areas in the sea were declared in Montenegro in 2021, namely. Nature Park "Platamuni", Nature Park "Katič" and Nature Park "Stari Ulcinj". These three nature parks represent integrated coastal and marine protected areas that fall into the IV category of protected areas, which includes areas where wild species of plants and animals are protected and their habitats are protected, and which are managed for their protection [13].

The management of protected areas in the zone of the marine resources is entrusted to the Public Enterprise for Coastal Zone Management of Montenegro[23] by the Law on Nature Protection (Official Gazette of Montenegro, No. 54/16) and Decisions on Proclamation of Protected Areas as Nature Parks. Decisions on declaring the protected areas to be the nature parks, as well as Decisions on internal order and protection services for all three parks, prescribe permitted and prohibited activities within the defined protection zones (zones II and III). The overview of permited and prohibited activities in these three MPA is given in Information produced by the Public Enterprise for Coastal Zone Management of Montenegro [13].

In all these areas, particularly in their water zones, the navigation of motor or sailing vessels is generally allowed, due to touristic purposes but it is not allowed to be on anchorage in these areas and to discharge the waste. Anchoring can cause mechanical damage to the seaweed rhizome grass *Posidonia oceanica*, but also waste water and others substances from the vessel (waste water, detergents, microwaste, etc). Namely, anchoring damages *Posidonia sea grass oceanica,* therefore in places where sea grass is present it is necessary to use spiral anchors with a buoy that lowers them mechanical damage to a minimum due to the small area which they include[24]. Among forbidden activities in Zone II are the movements of motor-driven vessels at a speed greater than ten knots, except for the official vessels of the management and competent

[23] https://www.morskodobro.me/

[24] Nature Park Platamuni – Management Plan 2023-2027, issued by Public Enterprise for Coastal Zone Management of Montenegro, Budva, June 2022.

services for the control of activities at sea[25]. In Zone III is allowed the navigation and stopping of motor-driven boats.[26]

Nature Park "Platamuni"

Nature Park “Platamuni“ park is an integrated coastal and marine protected area, between Trašte Bay - Cape Žabica in the northwest and Cape Platamuni (near Ploče beach) in the southeast (Figure 6 and Figure 7). By protecting this belt, protected and ecologically significant marine and coastal species and habitats are secured. Consequently, two protection zones (regimes) were defined - II and III protection zones, with prescribed permitted and prohibited activities [13].

Figure 5 - Logo of MPA Platamuni

The second (II) protection zone is defined only in the marine part of the Nature Park “Platamuni“ and occupies an area of 193.92 ha. Localities that belong to the II protection zone are:

- Žukovac cove with the surroundings of the Kalafat rocks(Seka Albaneze),
- Velika Krekavica cove and
- in front of the Cape Platamuni.

The third (III) protection zone is defined in the marine and coastal part, covering an area of 893.20ha and includes the following localities:

- the land part of the protected area that follows the coastline, including sea cliffs, but also rocks and steep slopes,

[25] Nature Park Katič – Management Plan 2023-2027, issued by Public Enterprise for Coastal Zone Management of Montenegro, Budva, January 2023.

[26] Nature Park Stari Ulcinj – Management Plan 2023-2027, issued by Public Enterprise for Coastal Zone Management of Montenegro, Budva, January 2023.

- the marine part of the protected area includes the seawater area between the coastal line and the 50m isobath, excluding locations set aside in the II protection zone.

Other important information about this MPA:

- Declaration date: 22.04.2021
- Area: 1.087,13ha
- (sea part 1.056,51ha, land part 30,61ha)
- Length of the border: 28,522km[27]

Figure 6 - Nature park Platamuni

(source [13])

[27] https://www.morskodobro.me/fajlovi/p1h3hh9d26751720n4g1k677fg4.pdf

Figure 7 - Nature Park Platamuni

(source [13])

Nature Park "Katič"

Nature Park “Katič” (Figure 9 and Figure 10) is an integrated coastal and marine protected area, which stretches from Skočiđevojka in the northwest, to Maljevik in the southeast, in which protected and ecologically significant marine and coastal species and habitats are protected. Consequently, two protection zones (regimes) were defined - protection zones II and III, with prescribed permitted and prohibited activities [13].

Figure 8 - Logo of MPA Katič

The second (II) protection zone is defined only in the marine part of the Nature Park “Katič“ and is divided into four spatial units occupying a total area of 276.90 ha. Localities that belong to the II protection zone are:

- the surrounding of the island of Mali Katič (Sveta Neđelja church) and Veliki Katič, the area which, towards the Petrovac bay, reaches a line that is 150m away from protruding land parts of Malo brdo and the Petrovac dock,
- zone in front of the southern part of the Buljarica Cove 150m distant from the beach itself, which in the direction of Dubovica includes the zone from the coastline to the wider zone of the sea rock the Mravinjak rocks,
- Perčin cove to Cape Kotrobanja, excluding the caostal zone in front of the beach itself (“Kraljičina plaža“) up to the boundary line which is 100m from the central part of the beach,
- Maljevik cove to the line Crni Cape – Cape Krčevac[28].

The third (III) protection zone covers an area of 2468.29ha and includes the following locations on land and sea [13]:

[28] https://www.morskodobro.me/fajlovi/p1h3hh9d26751720n4g1k677fg4.pdf

- The land part of the protected area that follows the coastline, including sea cliffs, rocks and steep slopes in five areas: Skočiđevojka-Petrovac, Malo Brdo, Velje Brdo, Dubovica and Crni rt (the borders of these areas toward the sea are limited by the coastline itself).
- The marine part of the protected area, which includes the seawater area between the coastal line and the 50m isobath, the separated zone in front of the beach in the Perčin bay up to the boundary line located at a distance of 100m from the central part of the "Kraljičina plaža" beach itself, excluding locations that are separated in protection zone II

Here are basic information about this MPA:

- Declaration date: 16.09.2021.
- Area: 2.744,93ha
- (sea part 2.568,67ha, land part 176,52ha)
- Length of the border: 35,808km [13]

Figure 9 - Nature park Katič

(source [13])

Figure 10 Nature Park Katič

(source [13])

Nature Park "Stari Ulcinj"

Nature Park "Stari Ulcinj" is an integrated coastal and marine protected area, which stretches from the southern side of Karastanov Cope in the north, to the northern end of Valdanos beach in the south, in which protected and ecologically significant marine and coastal species and habitats are protected. Consequently, two protection zones (regimes) were defined – protection zones II and III, with prescribed permitted and prohibited activities [13].

Figure 11 - Logo of MPA Stari Ulcinj

The second (II) protection zone is defined only in the marine part at the Nature Park "Stari Ulcinj", which is separated into two spatial units, which occupying a total area of 79.68ha. Localities that belong to the II protection zona are[29]:

• the surroundings of Stari Ulcinj island with the westernmost part of Hladna cove and the northern side of Kruče cove,

• coastal area of Mavrijan from cape Mavrijan to the northern end of Valdanos beach, including Cape Rep, Latova njiva cove, Udovica cove and Vučija jama cove.

The third (III) protection zone covers an area of 847.78ha and includes the following locations on land and sea:

• The land part of the protected area that follows the coastline, including sea cliffs, rocks and steep slopes on the stretch from Karastanovo rt to Valdanos beach,

• The marine part of the protected area that includes the water area between the coastal line and the administrative border of the protected area, which is at a distance of about 1NM, excluding locations that are set aside in the II protection zone [13].

[29] https://www.morskodobro.me/fajlovi/p1h3hh9d26751720n4g1k677fg4.pdf

Here are basic information about this MPA:

- Declaration date: 29.12.2021.
- Area: 929,16ha
- (sea part 910,42ha, land part 17,03ha)
- Length of the border: 17,62km

Figure 12 - Nature park Stari Ulcinj

(source [13])

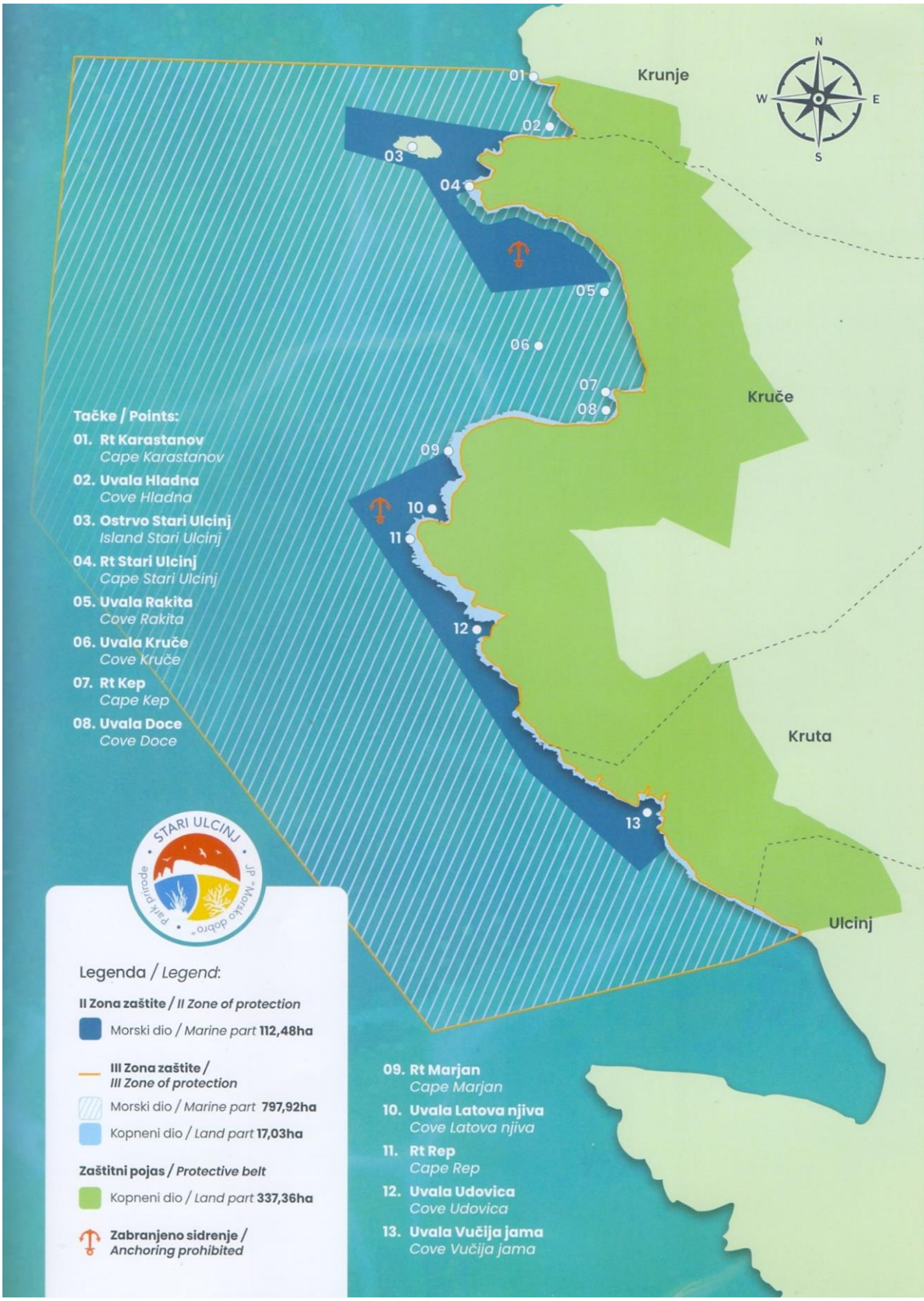


Figure 13 - Nature park Stari Ulcinj

(source [13])

ZONE II - Permitted / prohibited activities

Having in mind that national laws on these areas stipulate which activities are allowed to be done in marine protected areas and recognising the division of the overall areas in zones II and III, here we give an overview of permitted and prohibited activities in all marine protected areas in Montenegro, based on Management plans and information materials[30].

Permitted activities

• commercial and sport-recreational fishing with floating longlines and fishing tools that do not touch the seabed and do not damage species and habitats on the seabed, and in accordance with the conditions issued in the fishing permits, giving priority to holders of commercial fishing permits;

• setting up and using underwater diving paths for nature interpretation - a maximum of two paths in separate parts of the II protection zone, which will be determined based on the appropriate expert basis of the Program of temporary structures in the coastal zone, the Management Plan and based on the previously obtained approvals;

• controlled scientific research and monitoring of natural processes based on the permission of the Environmental Protection Agency and the approval of the Manager;

• controlled visits for educational, recreational and tourist purposes, exclusively in part II of the protection zone, which will be determined on the basis of the appropriate expert basis and based on the of previously obtained approvals [13];

Prohibited activities

• fishing, with the exception of fishing with floating longlines and fishing tools that do not touch the seabed and do not damage species and habitats on the seabed, and in accordance with the conditions of fishing licenses, giving preference to holders of licenses for commercial fishing;

• use of natural resources;

• vessel anchoring;

• movement of motor-driven vessels at a speed greater than ten knots (10 kn), except for the official vessels of the Manager and competent services for controlling activities at sea;

[30] Information about permitted and prohibited activities in Nature Parks „Platamuni“, „Katič“ and „Stari Ulcinj“, issued Public Enterprise for Coastal Zone Management of Montenegro in 2022.

• mariculture;

• installation or construction of facilities;

• changing the use of surfaces;

• dispersing, capturing, harassing and killing animals and plant species;

• settlement of non-native and invasive species;

• undertaking works that could lead to damage to species and habitats and archaeological values;

• the use of substances that can threaten the vitality and fundamental natural values of the marine ecosystem;

• accidental or intentional disposal or rejection of communal and any other waste;

• damage to underwater geological and geomorphological values;

• impoverishment of the natural stock of wild species;

• pollution or endangerment of the sea [13];

ZONE III - Permitted / prohibited activities

Permitted activities

• economic and sport-recreational fishing, in accordance with the regulations governing sea fishing, until the conditions for introducing restrictions are met, based on scientific data of targeted research of fishing resources in the protected area, which are defined by the Management Plan, fishing permits, and regulations in the field of marine fishing;

• movement and stopping of motor-driven vessels;

• use of pedestrian and recreational trails on land in accordance with the Management Plan and based on the previously obtained approvals;

• scientific research and monitoring of natural processes [13].

Prohibited activities

• placing or building facilities that pollute, damage, or threaten the marine and coastal ecosystem, natural habitats, and species;

• changing the use of surfaces;

• dispersing, catching, harassing, and killing animal species;

• settlement of non-native species [13].

3.3 Fuel minimisation

The Fourth IMO GHG (Greenhouse gas) Study 2020 [14] has estimated that shipping has emitted 1065 million tonnes of CO_2 in 2018, which accounts 2.89% of the global anthropogenic CO_2 emissions for that year [31]. The initial GHG strategy envisages, in particular, a reduction in carbon intensity of international shipping (to reduce CO_2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008); and that total annual GHG emissions from international shipping should be reduced by at least 50% by 2050 compared to 2008 [32].

The drive to optimize fuel consumption resonates as an essential concern in an age of resource scarcity and environmental consciousness. As maritime transport accounts for a substantial portion of global greenhouse gas emissions, the industry's evolution towards sustainability hinges upon innovative strategies to curtail fuel consumption. This imperative extends beyond economic considerations, becoming a pivotal element in achieving international emissions reduction goals and fostering a greener future for maritime operations.

To address this intricate confluence of challenges, a multidisciplinary approach is essential. Modern navigation and communication technologies, predictive weather analytics, real-time data integration, and advanced computational models collectively provide ship captains, operators, and regulators with a toolbox to navigate through the complex interplay of maritime logistics, risk management, and fuel conservation. These tools empower decision-makers with actionable insights, allowing them to chart routes that minimize exposure to hazards, optimize fuel usage, and promote overall operational efficiency.

Reduced fuel usage leads to reduced emissions and decreases the impact on the environment, lowering shipping companies' costs. Although to operate a ship in a fuel-efficient way, while considering safety and time constraints, can be a challenging task, with many dynamic parameters to consider. This initiative demonstrates how software and data can be utilized to aid in that task.

By dissecting the intricate web of variables that dictate the optimal course for vessels carrying dangerous cargo, we aim to illuminate the evolving strategies that harmonize safety, environmental consciousness, and economic viability. The endeavour is to contribute to the ongoing discourse surrounding the maritime industry's transformation—a realm where the quest for the shortest, safest route converges seamlessly with the imperative to chart a course toward sustainable navigation and responsible resource utilization.

[31] https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.19(22).pdf

[32] https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx

Nowadays AI-driven propulsion control systems are developed, that can process large amounts of information, like forecasts of wind, current and waves, physical specifications of the ship, depth and draft, to make quick decisions on the best route and how to operate the propulsion power in a fuel-efficient manner.

4. SOLUTION FOR FINDING THE SHORTEST AND SAFEST MARITIME ROUTE FOR DANGEROUS CARGO

4.1 GENERAL DESCRIPTION OF SHORTEST PATH PROBLEM

Maritime transport involves navigating ships from one port or location to another over short, medium or long distances. The general objective is to find the most efficient route between two points, taking into account various constraints and parameters. The shortest path problem in maritime transport seeks to determine this most efficient route. In other words the objective is to find the route that allows a ship to travel from a starting point (origin) to a destination in the safest possible manner with the minimal cumulative cost. While "shortest" often refers to distance, it can also mean the quickest route in terms of time, or even the least expensive in terms of fuel consumption or other costs.

There are lot of parameters and constraints that could influence in finding the shortest path and safest path in maritime transport and here some will be mentioned:

- Geographical parameters represented in physical constraints such as shoals, islands, and icebergs that the vessel needs to avoid;
- Meteorological parameters represented in weather conditions like storms, currents, tides, and winds that can influence the chosen path;
- Maritime Traffic parameters as the presence of other vessels, especially in congested sea routes, which can affect the choice of path;
- Legal and Political parameters such as territorial waters, marine protected areas, war zones and political disputes can restrict certain paths;
- Ship specifications such as ship size, draught (how deep the ship sits in the water), and type can limit which routes are feasible.

There are many applications of the Shortest Path Problem in maritime transport. For commercial vessels is important to ensure timely and cost-effective delivery. In this way the route planning influence the cost of transport and also marine environmental protection. Also SAR authorities can benefit to determine the quickest route to reach a distressed vessel or person. From environmental perspective, in case of an oil spill or similar disaster, determining the quickest or most efficient response route is from crucial importance.

The problem can be represented using a graph, where ports or waypoints are nodes, and the paths between them (considering all constraints) are edges. The weight on these edges can represent distance, time, cost, etc. Classical algorithms like Dijkstra's, A (A Star)* or other can be used to solve the problem. For real-time solutions, especially with dynamic parameters (like changing weather conditions), more advanced heuristic or metaheuristic methods might be employed.

In essence, the shortest path problem in maritime transport is critical to ensuring efficient, safe, and cost-effective navigation across the vast and complex marine environment.

4.2 Navigation path introduction

Defining the navigation path in maritime transport is the science of planning and controlling the movement of a vessel from one point to another. The purpose of defining the navigation path is ensuring safe and efficient vessel movement from departure to destination. During the history navigational methods have evolved from basic observations to advanced electronic systems. Many aids have been produced during history to enable safe maritime transport navigation route as:

- Nautical Charts: Paper charts and Electronic Navigational Charts (ENCs), which how depths, land contours, navigation aids, obstructions, shipping routes, and other pertinent information.
- Navigation Aids as Buoys & Beacons (Floating or fixed aids with specific shapes, colours, and light characteristics), Lighthouses (Structures with a powerful light to aid navigation at night) and Radar Beacons (RACONs) which transmit identifiable signals when hit by radar waves.
- Instruments for navigation like:
  - Compass: Magnetic and gyroscopic compasses to determine direction.
  - Radar: Uses radio waves to detect objects and determine their distance and position.
  - ECDIS (Electronic Chart Display and Information System): A computer-based navigation system displaying ENC data and vessel's position.
- Systems for Satellite Navigation:
  - GPS (Global Positioning System): Provides accurate position fixes using satellite triangulation.
  - GLONASS, Galileo, BeiDou: Other satellite navigation systems from Russia, Europe, and China respectively.

Also Marine Pilots have been introduced as experienced mariners who guide ships through dangerous or congested waters, such as ports or narrow straits.

Many safety considerations and international instruments are in place (in addition to adequate tools) to secure safe navigation, such as:

- COLREG rules for collision Avoidance: Using tools like the Automatic Identification System (AIS) and radar.
- SOLAS (Safety of Life at Sea): An international maritime treaty that sets safety standards for vessels.

When the navigation path is calculated, also environmental considerations should be taken into account, such as:

- Marine Protected Areas: Zones where ship movement might be restricted to protect the environment.
- Ballast Water Management: Preventing the transport of invasive species.

As technology progresses also maritime navigation tools and methods will be improved. Modern technological advancements are for example:

- Autonomous Vessels: Ships that can operate without human intervention.
- Augmented Reality (AR) for Navigation: Overlaying real-time data on visual displays.

Safe and efficient navigation is vital for global trade and commerce.

4.3 Commonly used algorithms for shortest path and time complexity

In this section the review related to multimodal safest and most efficient path or navigation route optimization algorithm design is given. Here is described and presented some of the most important current achievements in development of mathematical models for the purpose of making navigational routes for multimodal and intermodal transport safest, shortest and cost-effective as much as possible for shipping companies and other logistics stakeholders.

Three main groups of algorithms and its applications in multimodal transport modelling have been considered:

1. Dijkstra’s algorithm,
2. A-star Algorithm,
3. Bellman – Ford algorithm
4. Other algorithms.

Also, in this section are mentioned and described some practical solutions and software applications for shipping routes navigation optimisation in the form of VISIR and SeaConditions platforms.

4.3.1 Dijkstra’s algorithm

Dijkstra's algorithm, developed by computer scientist Edsger Dijkstra in 1956, is a tried-and-tested method for finding the shortest path between nodes in a graph. In the context of maritime transport, these nodes represent specific geographic locations or waypoints, and the edges represent navigable routes between these locations[33]. The weights assigned to these edges can represent various factors such as distance, time, or fuel consumption, among others.

In the world of maritime transport, Dijkstra's algorithm can be instrumental in determining the most efficient path for a ship to traverse from its origin to destination. By modelling the oceanic routes as a weighted graph, where weights could represent the distance, anticipated travel time, or even the fuel costs associated with traversing between specific waypoints, Dijkstra's algorithm systematically explores all possible paths to identify the one with the minimum cumulative weight.

The adaptability of the algorithm allows for the incorporation of dynamic variables such as weather conditions, sea currents, and obstacles, offering real-time optimal path solutions that are both cost-effective and safe. Each edge's weight can be adjusted to reflect the real-time conditions, ensuring that the selected path is not just theoretically optimal but is also practical and safe under the prevailing circumstances.

First of all, the Multimodal transport network could be defined as the combination of two or more means of transport to move passengers or goods from one source to a destination. In [15] A. Idri et al. discussed a new time-dependent shortest path algorithm for multimodal transportation networks, pointing out that the shortest path problem for a transportation solution is a classical combinatorial optimization problem with many applications. Solving the multimodal route planning is a highly important issue to develop seamless advanced traveller information systems. So far, the most common method for calculating the shortest path between two points and places is the classical **Dijkstra's** algorithm, but now it is provided a more appropriate algorithm that is in essence the goal-oriented single-source single-destination algorithm. It means that the concept of "closeness" to the target node as a heuristic to drive the search towards its destination, is a core element of this algorithm. Other methods used for the shortest and safest paths design are hypergraph theory, multi-label networks, dynamic algorithms to cope with the time dependency aspect of public transportation modes, and Genetic algorithms. The main idea behind the algorithm approach is to explore the nodes in a restricted search space defined by certain parameters and calculated in a specific procedure. Using other methods, the proposed algorithm performs the following actions [15]:

- Compute the virtual path $distance\ (s,\ t) = D$ and the constraint parameters d and Δd;
- Launch the search process restrained into the reduced search space $(2d, D)$ and start to construct the path with edges that satisfy the condition $\forall v_i \in V,\ dist(v_i, (st)) \leq d$;
- apply the elementary step function that applies a multimodal time-dependent shortest path algorithm to find the next candidate vertex for the next iteration;
- Increase the parameter *d by* Δd when no vertex satisfies the constraint above, in order to extend the search space and reiterate the search process to find other candidate vertices for the constructed path [15].

In [16] Dijkstra's algorithms were used, together with the Breadth-First and Bellman-Ford algorithms to calculate the shortest routes between Turkish and Greek ports in Aegean Sea, and the results were evaluated in terms of the route, distance and calculation time used. The Dijkstra algorithm is also used to identify the

33 https://en.wikipedia.org/wiki/Dijkstra%27s_algorithm

most used route by ships between two locations and the average speed profile for any possible path within the graph, simply by using historical AIS data [17].

Dijkstra’s algorithm stands as a foundational tool in the arsenal of maritime navigational optimization techniques. Its simplicity, efficiency, and precision make it a go-to solution for straightforward shortest path problems. As the maritime transport industry evolves, integrating Dijkstra’s algorithm with other optimization techniques and real-time data analytics could enhance its applicability, making it an integral component of a holistic maritime navigational optimization strategy.

4.3.2 A-star algorithm

Path-planning algorithms are pivotal in numerous applications, from computer games to robotics and to maritime transport. Path planning is crucial in the development of autonomous systems for ships and it serves as the foundation for ship systems [18] [19].

Among these algorithms, the A-Star (A*) algorithm is one of the most versatile and widely accepted solutions for many pathfinding and graph traversal tasks. In the context of ship navigation and path planning, A* can be uniquely adapted to provide efficient, safe, and optimized routes, considering the specialized challenges that marine vessels encounter. There are many proposed improvements in the ship path-planning problem, but they do not consider the impact of the marine environment on ship navigation [20].

A* is an informed search algorithm, which means it employs heuristics to estimate the cost from the current node to the goal, allowing it to prioritize paths that are more likely to result in a shorter path. Fundamentally, it operates by traversing a graph and using two main costs:

- the known cost from the starting node to node n.
- the estimated cost from node n to the goal (heuristic).

The sum of these costs estimates the total path cost through node n.

While A* can be employed generically across various domains, ship path-planning has specific considerations such as:

- Dynamic Obstacles: Unlike static landscapes, marine environments are filled with moving obstacles like other vessels, drifting icebergs, or floating debris. A* can be adapted to consider these dynamic elements by frequently updating the navigation graph [21].
- Environmental Factors: Ships must contend with marine currents, winds, and tides that can impact their course. An A* algorithm for ships might incorporate these environmental factors into the cost functions to select the most energy-efficient or time-efficient path [22].
- Draft and Size Considerations: Larger ships with deeper drafts might be unable to navigate certain shallow areas. A* can account for this by marking nodes or areas in the graph as non-navigable for specific vessels.

- Turn Constraints: Ships, especially larger ones, cannot make sharp turns. Therefore, any A* adaptation must consider the curvature constraints of the vessel's path.
- Safety Buffers: Given the high stakes of maritime navigation, paths generated must incorporate safety buffers, ensuring ships remain at a safe distance from obstacles and other vessels.

The A-star algorithm is lately used in path planning because of its high level of completeness and optimality, but if used in isolation, it can lead to paths that overlook environmental factors, and demonstrate poor algorithm efficiency [23]. In [22] and [24] the A-star algorithm is used, and also the factors are examined that influence the ship navigation safety, by developing a risk model that takes into account water currents, water depth, traffic Separation and obstacles.

In conclusion, with its adaptability and efficiency, the A-Star algorithm can be effectively employed for ship path planning by integrating marine-specific factors into its computation. The outcome is a dynamic, real-time, and safe navigation solution suitable for the ever-evolving challenges of the maritime world.

4.3.3 Bellman-Ford algorithm

The Bellman-Ford algorithm, named after its developers Richard Bellman and Lester Ford, is a graph-based method used to find the shortest paths from a single source node to all other nodes in a weighted graph. Unlike Dijkstra’s algorithm, Bellman-Ford can handle graphs containing negative weight edges, making it versatile in applications where costs or weights can fluctuate[34].

In maritime transport, the ocean, ports, and other navigational points can be represented as a graph where nodes represent specific locations and edges represent the routes connecting these locations. The weights of the edges could be determined by various factors such as distance, travel time, fuel consumption, or even the associated costs of traversing particular routes.

One of the features of the Bellman-Ford algorithm is its capability to accommodate negative weights [25]. Unlike Dijkstra's Algorithm, the Bellman-Ford Algorithm can deal with negative edge weights, and will detect if there exists a path with a negative edge cycle [26]. In maritime contexts, this can be particularly beneficial when considering dynamic pricing or fluctuating costs associated with certain routes, potentially allowing for more cost-effective navigation. Also, the Bellman-Ford algorithm works well on networks with small shortest paths tree depth [27]. In finding the optimal route in the multilayer data transmission network, the best performance was shown by the Bellman–Ford algorithm without pre-processing, because additional methods require additional time costs [28].

Maritime transport is characterized by a multitude of variables, including changing weather conditions, sea currents, and geopolitical factors, each impacting the optimal route at any given time. The Bellman-Ford algorithm can be recalibrated with updated weights to reflect these real-time changes, providing an adaptive mechanism to constantly seek the most efficient path under prevailing conditions. Furthermore, the Bellman-Ford algorithm is adept at identifying negative cycles - loops in the graph where the total sum of the edge

[34] https://en.wikipedia.org/wiki/Bellman%E2%80%93Ford_algorithm

weights is negative. In practical terms, this feature could be used to identify and avoid routes that could lead to repetitive, non-productive, or even hazardous navigation patterns.

However, the Bellman-Ford algorithm is not without its limitations. It tends to be slower than Dijkstra's algorithm and can be computationally intensive, especially for larger graphs [29]. In the vast and intricate landscape of maritime transport, computational efficiency is a critical factor to consider.

In essence, the Bellman-Ford algorithm emerges as a valuable tool in the maritime transport sector for its ability to accommodate dynamic and negative weights and its adaptability to real-time changes. By integrating this algorithm with modern computational technologies and real-time data analytics, maritime operators can potentially enhance navigational accuracy, safety, and efficiency, even in the face of the unpredictable and ever-changing conditions of the open sea.

4.3.4 Solving optimal path using multi-objective optimisation algorithm

Path optimization is considered a multi-objective optimization problem, and the optimization result is affected by several factors such as transportation cost, time, and risk. The optimization of the plan concerning the derived single-objective problem is expected to realize a win–win situation among stakeholders. Therefore, in [30] the authors (Lu and Wang) propose the model to find a solution with the optimal result that considers the comprehensive factors so that the single objective function transformed from the multi-objective function is optimal. The specific algorithm steps are as follows [30]:

1. Build a multi-mode transportation network. First, find a feasible path from the transportation starting point to the endpoint based on the open-source map. Then, label the starting point, the endpoint, and transit point, divide the transportation network into *V* stages, and mark each stage's path length and transportation mode.

2. On this network, calculate the optimal path with the shortest transportation distance, the minimum transportation risk, and the shortest transportation time as the single objective. If the three paths are the same, determine that the path is optimal and end the algorithm; otherwise, go to step 3.

3. Calculate the total index value (which includes distance, risk, and time) of each road section and select the optimal path.

Step 3.1: Write the index value matrix of all road sections $A = (a_{ij})\ m \times n$, where m and n are the number of start site i and end site j, respectively. Among them, to eliminate the influence of dimension and make different variables comparable, the index value matrix should be normalized to $R = (r_{ij})\ m \times n$, and the processing method is $r_{ij} = (a_{max} - a_{ij})/(a_{max} - a_{min})$.

Step 3.2: Obtain the total index values (in terms of transportation distance, risk, and time) of different paths according to different weights assigned to indexes, which decide the relative importance of transportation distance, risk, and time. Select the path of the smallest total index value as the optimal path [30].

Following this algorithm, the corresponding set of formulas is given in [30].

For this purpose it is used the Dijkstra's algorithm, as a method for the shortest path in graphs, especially for weighted graphs. It is only suitable for finding the shortest path with positive edge weights. Generally, it is a single-source-directed weighted graph. This shortest path algorithm goes from one vertex to the other vertices, which solves the shortest path problem in the weighted graph. The main feature of **Dijkstra**'s algorithm is that it starts from the starting point and adopts the strategy of a greedy algorithm.

Therefore, the single transportation plan needs to determine the risk, time, and cost models. The risk model mainly describes the probability of danger in the transportation process and the consequences after the threat. The measurement indicators are the probability of an accident in the path, population density, and emergency rescue. Transportation time comprises loading and unloading time, transportation time, and typical scene delay time. The delay time mainly includes sea ice, fishing season, ocean currents, and typhoons, which may be encountered in maritime transportation. Transportation cost is an essential condition that needs to be controlled in the transportation process, mainly including personnel, container, equipment, and transportation tool costs.

Another important thing, the method of Fuzzy eclectic planning is here implemented as one of the previously widely used shortest path algorithms. It aims to blur the boundaries of linear constraints so that people can find optimized conditions and extremums under more relaxed conditions. This approach uses the gradient descent algorithm to solve the large-scale transportation optimization problem and search for the optimal solutions. The method addresses the transport of dangerous goods under multi-modal transport conditions, with the transport process covering three modes of transport: sea, road, and rail. The method calculates the most suitable transport solution based on three influencing factors: transport cost, transport risk, and transport time, and it's designed to help transport decision makers to develop transport solutions that include the generation of transport routes and the deployment of transport resources, as well as individual transport solutions that include schedules, layouts, and transport overview maps.

The new approach for multimodal routes optimization is described in [31], introducing the User-Constrained Contraction Hierarchies (UCCH). The algorithm for UCCH starts with pre-processing going to the query algorithm afterwards. The query algorithm for optimal routes combines the concept of a multimodal Dijkstra algorithm with unimodal Contraction Hierachies (CH). In this research, the mentioned author, presents the improvements to proposed algorithm, some of which also apply to CH. Its advantages in term of optimization algorithm are related to average vertex degree, edge and vertex ordering, core and state pruning, state-independent search in component, and parallelization.

4.3.5 Genetic algorithm and other important algorithms

For multimodal transport problems solving, many researches have been done in the previous decade. Among these, the most important ones propose the opportunity constrained programming model of multimodal transport, the minimization of transportation cost and transhipment cost as the objective function to construct a mathematical programming model for multimodal transport path selection, a 0-1 planning model for multimodal transport hub location, and maybe the most essential, a multi-objective optimization model for multi-modal transport path selection considering multi-commodity flow. This model considers time window constraints, transportation mode selection, and transportation cost. Following these proposals for multimodal transport optimization problem solutions, in the paper of Zhou, Du [32], the **genetic algorithm** is used to solve the model mainly in six steps: Code Design, Determination of population size, Design of fitness function, Select an action, Cross operation, and Mutation operation. This approach considers the requirements of logistics cost and timeliness, time window, and multimodal transport problem, presenting the advantages of the three modes of transportation, thus reducing the total logistics cost. The results show that the model and algorithm are feasible and practical in multimodal transport.

Mathematical models of multimodal transportation, proposed in the paper of Zhao [33] are built by integrating transportation cost, conversion cost and punishment cost of time based the comparison of various modes of transportation. The model solution algorithm uses an improved **Genetic Algorithm** with added immigration factor, which can ensure diverse population and enhance search abilities. Example results show that port logistics multimodal transportation network operation cost is reduced by 45.8%. To calculate the relations between multimodal transport modes and to find an optimal rate of costs, time, efficiency and other factors, a mathematical model of for transportation networks have been designed. The problem is schematically shown in Figure 14 - Schematic diagram of multimodal transport network path Figure 14.

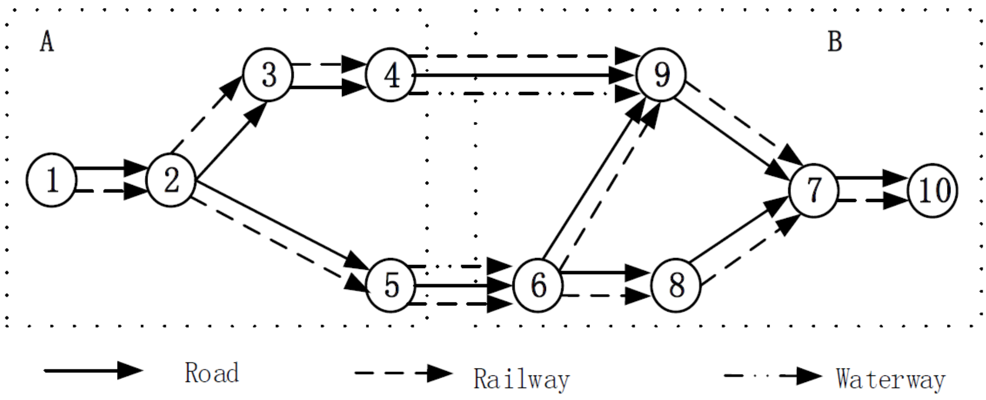


Figure 14 - Schematic diagram of multimodal transport network path

(Source [33])

Figure 14 shows the schematic diagram of multimodal transportation which is from the Node city 1 of port hinterland A to the Node city 10 of port hinterland B, among them, the mode of transportation between two nodes is greater than or equal to two types. In the process of looking for the shortest path between node 1 and node 10. It not only needs to find out the nodes cities, but also choose the transportation mode between every two nodes. Because of multitudinous logistics nodes and numerous transportation modes, the problem of multimodal transport network is a very special and complex shortest path problem. There have been defined the objective function which mainly contains two parts. The first part is the total cost of transportation, and it includes the cost of transportation, loading and unloading.

An interesting case study concerning these matters is done in [33], on the example of Chinese cities and ports. The previous transportation mode of the seaport logistics company in Zhejiang province is distributing motor vehicles by cargo traffic between two points, then the motorcade directly starts off from the point of departure to the destination, and this mode of transportation is a single mode of direct transports. The total cost of highway single mode of transportation that is using MATLAB to solve is 37,092,000 yuan. Through the construction of multi-modal transport logistics network, Different o-d pairs of modes combination need to be chosen for the shortest path at the lowest cost. According to the solution results, the path of each o-d pair is shown in Figure 15.

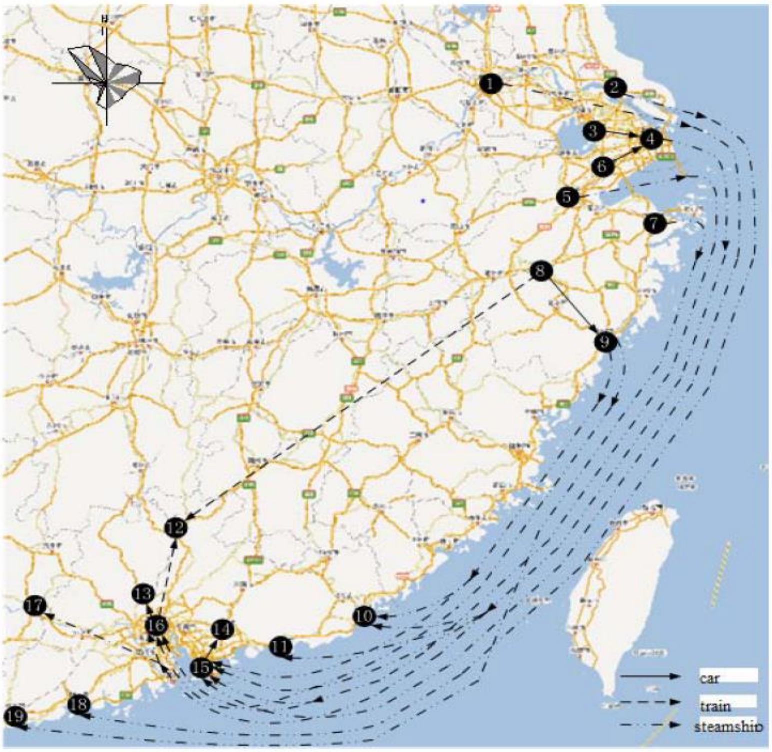


Figure 15 - Optimal path diagram of multimodal transport network

(Source [33])

Routing planning is a kind of combinatorial optimization problem that is related to the optimal utilization of the resources in a system. By selecting optimal routes to distribute the flow of the objects (e.g. commodities, products, data, signals, etc.) in systems, the performance of the systems can be improved efficiently from many view-points (economy, stability, timeliness, etc.). For multi-modal transportation, freight routing planning refers to the combinations of various transportation modes (rail, road, water and air) to generate origin-to-destination routes to move commodities through the multi-modal transportation networks. The truck-rail and rail-ocean combinations are the prevalent manners in the practical multi-modal transportation.

Optimization models are formulated to describe the multi-modal transportation freight routing planning problem mathematically. By inputting the practical transportation data into the optimization models and then solving them by exact solution methods (e.g. column generation method and branch-and-bound method) or approximate solution methods (e.g. Genetic algorithm and Tabu search algorithm), optimal solutions can be attained and can provide decision makers with quantitative decision support.

The multi-modal transportation freight routing problem is known as a kind of NP hard problems, and this characteristic has also been verified, i.e. the optimal solutions of the large-scale or real-world freight routing planning problem are hard to be attained by the single exact solution methods, while the heuristic algorithms proved good feasibility in solving the optimization models, e.g. Genetic algorithm, PSO algorithm and ACO algorithm, etc. , as shown in literature review by Sun, Lang, Wang in [34].

Among the various heuristic algorithms, **Genetic algorithm** is the most classic and popular one. A good understanding of the Genetic algorithm can help us capture the essence of the heuristics. The basic components of the Genetic algorithm are stated as follows [34]:

(1) Representation of the solutions

(2) Evaluation of the solutions.

(3) Updating strategy

(4) Termination criterion (Genetic algorithm terminates after evolving a certain number of generations (iterations)).

Above all, the flowchart of the Genetic algorithm is shown in Figure 16.

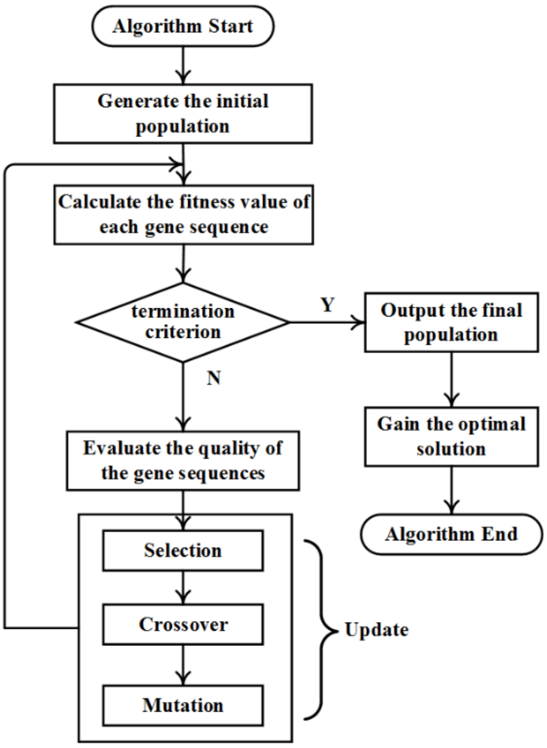


Figure 16 - Flowchart of the Genetic algorithm

(Source [34])

As it can be seen from the progress of current studies, almost all of them simplified the multi-modal transportation freight routing planning problem excessively. Regarding this matter, there are some great challenges for the researchers such as: (1) mathematical description of the transhipments among the multiple services; (2) formulation of the time related inventory capacity; and (3) stochastic analysis that needs massive reliable statistical data. To conclude with, freight routing planning problem in the multi-modal transportation network still has large research potential that needs to be explored.

Multimodal transport is potentially more feasible as it saves cost and lower environmental effects. The research conducted in [35], consists of investigations of freight transport and logistics framework for advancing the sustainable multimodal freight delivery involving road, rail, and waterway in an inland transportation. The optimal design system is modelled by adapting **Genetic Algorithm** (GA) and Matlab software to improve the existing transport split modes with high shipment cost, considering the time, distance, and CO_2 emissions, as well. The output of this paper is the optimized sustainable multimodal freight transport and logistics system (SMFTLS) in the form of a model for multimodal transportation to and from national ports. The aim is to make an optimal sustainable multimodal freight transport and logistics system (SMFTLS) framework and to promote feasible freight transport and logistics system, which considers the costs of distance, time, and CO2 in the optimization process. The sustainable multimodal freight transport and logistics system (SMFTLS) is illustrated in Figure 17.

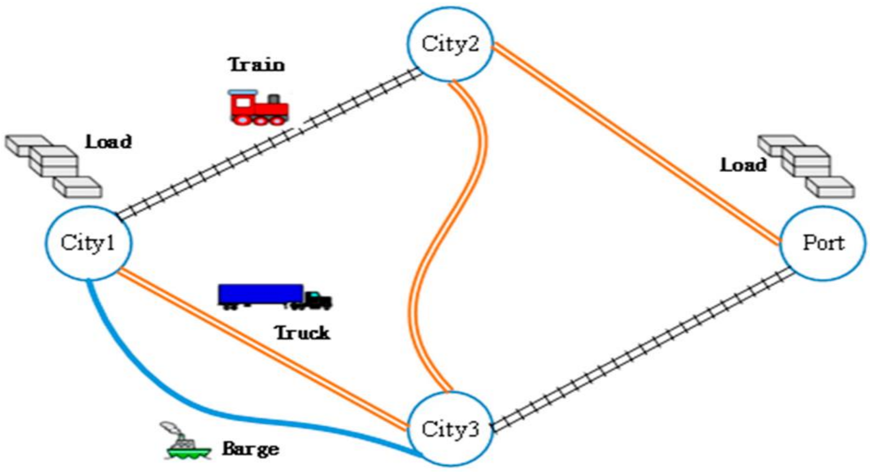


Figure 17 - Description of SMFTLS network

(Source [35])

As could be seen in Figure 17, barges, which have a huge vehicle capacity regarding transport units; rail, which has a large vehicle capacity (although lower than barges); and exchanges are the three means of transportation accessible. Only one transport unit can be transported in the latter mode. Loads are transported straight from the city terminal to the port or via multiple city terminals to the port and back. Each of the three modes employs different independent linkages. This model has several variables, which will be briefly summarized as follows:

- A transport demand TD is provided, as is customary in container shipping, and is thought to be separated into a number of generic, interchangeable units.
- Transportation demand is also uniform, with greater demand having a similar time horizon of the earliest achievable departure time, the latest possible departure time, and the optimal arrival time.

- Every mode consists of a set of free-flow travel time (FFTT), which is the shortest possible travel time devoid of congestion effects; and a travel-related price, P, which changes depending on the mode and distance.
- Expecting costs definition.

In general, used units and reference parameters defined in this model are the following: Set of the cities, Set of the modes, Mode of the vehicle (truck/train/barge), Cities in the transportation network, Distance of city *i* and city *j* Km, Transportation volume from city *i* to city, Transport from city *i* to city *j* choose mode *k*, Transfer from mode k to mode *l* in city *I*, Cost per unit load per kilometre per mode *k*, Cost per unit load of transfer from mode *k* to mode *l*, Transportation speed per mode *k*, Transfer time per unit from mode *k* to mode *l,* Cost of time per Unit load, Vehicle capacity per mode *k*, Carbon emission per kilometre per mode *k*, Cost of CO2 emission per *Kg*, and Total transport demand.

The method used in this research is based on Genetic Algorithms (GA), which is in fact the adaptive probability optimization algorithm founded on biological evolution and genetic mechanism. It has good adaptability to the optimization ability of many artificial systems.

Finally, it could be concluded that This SMFTLS model is relevant to recent technology and has logistics-based applications to help stakeholders and policymakers in their efforts to sustainably manage overall freight transport and logistics costs when considering the economic, social and environmental impacts.

To optimize the largescale complex multimodal transport path in an efficient and accurate manner, in the research [36], it has been used the **genetic algorithm** (GA) , embedded into the ant colony optimization (ACO), with creation of a dual pheromone hybrid algorithm.

Container Multimodal Transport (CMT) is so efficient that its standard logistics system can organically integrate multiple transport modes to achieve seamless joint of all logistics chains. Today, with the further development of “The Belt and Road” strategy, the CMT will usher in a new development opportunity.

In the research results, it is stated that the hybrid algorithm converged to the optimal solution through 46.17% and 45.25% fewer iterations, and lowered the transport cost by 4.23% and 2.39% than the GA and ACO, respectively. These results have been obtained by the following algorithm description. For this purpose, the GA-ACO hybrid algorithm is designed to solve the above problem. The dual pheromone matrix used for searching stores the paths and transportation modes separately Figure 18.

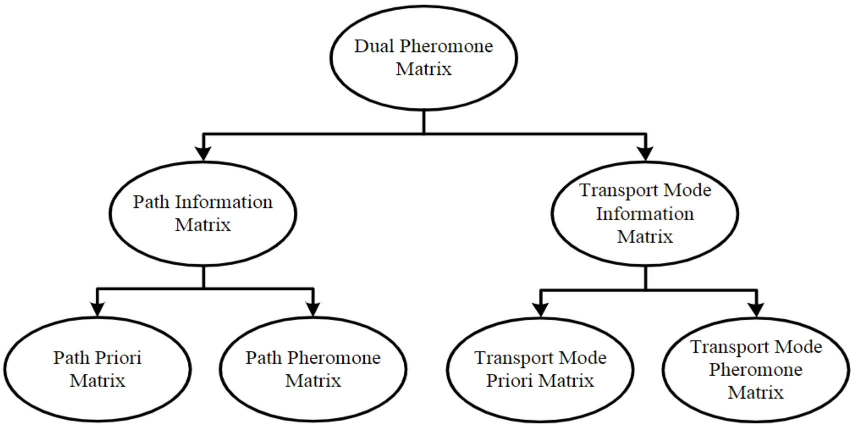


Figure 18 - Information storage structure for dual pheromone hybrid algorithm

(Source [36])

The hybrid algorithm first uses the GA to generate better individual, records the combination of its path and transport mode, and used it as update basis for initial parameters of prior matrices of initial path and transport mode. Then, the ant colony generate the path and transport mode selection probabilities based on the prior and pheromone matrices, and select the next node and the transport mode using the roulette until the destination. The path and transportation mode pheromone matrices are updated with the results of every generation of elite ants, and the adaptive catastrophe operator is referenced based on the max and min ants to dynamically adjust the pheromone matrix and allow it timely jump out of the local optimum solution generated by the GA, narrow the gap between the best and the worst individual pheromones, enhance the random option of the ant colony for paths and transport modes, and improve the global search ability. The process of the hybrid algorithm is shown in Figure 19.

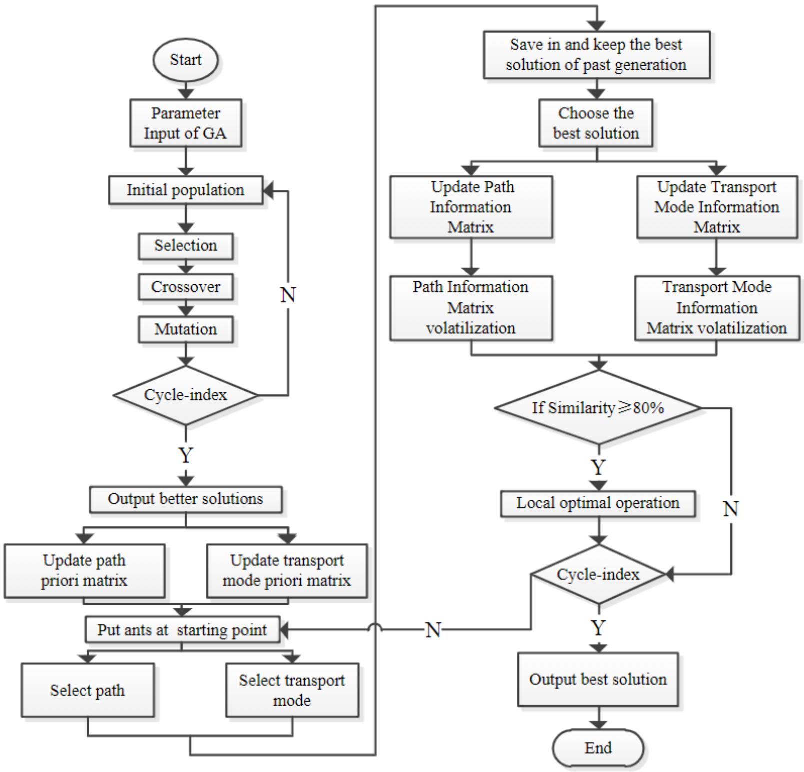


Figure 19 - Process of dual pheromone hybrid algorithm

(Source [36])

Some general conclusions of the complex algorithm described in Figure 19 are the following [36]:

1. The combined optimization model is established to minimize the transport cost, considering the "scale effect" of the transport economy, based on the practical operation of multimodal transport and customer demand, and with a constant piecewise linear function as the transport cost.
2. In view of the good global search capacity of genetic algorithm in early stage and the strong convergence of positive and negative feedback in the late stage of the ACO, the dual pheromone hybrid algorithm is designed with the solutions of rapid convergence.
3. To avoid the hybrid algorithm trapping in the local optimal solution, the dynamic genetic operator is designed in the genetic algorithm; the adaptive catastrophe factor is introduced in the ant colony optimization process, and the jump operation is randomly selected to improve the global optimization capacity of algorithm based on the population diversity.
4. The feasibility and efficiency of the algorithm is further tested with a case, and the different results of path selection under different constraints are discussed in detail. The assumptions are made on the transhipment process hereof. The model does not describe the practical

transhipment process in detail. When the transhipment cost and constraints change greatly, it should be further improved.

There are also other papers and scientific papers dealing with solutions for finding safest and shortest path in maritime transport.

In THE [37] the multimodal transportation network design problem is considered a discrete network design problem (DNDP). Here is proposed an approach of multimodal super network topology that includes four types of links (entering links, leaving links, driving links, transfer links), which clearly expresses inter-modal transfers among means of transit networks, as well as inter-route transfers in intermodal transfer.

In the [38] Liu and Meng propose a solution which can find the optimal route in a static N-modal network for an arbitrary mode combination, where N indicates the number of modes.

Graph theory is used to model typical travel behaviour within a multimodal network. Specifically, in the research [39] the use of special network modelling elements, e.g. super nodes, is proposed to allow the integration of public transportation schedules into the model via the publicly available predefined timetables. The proposed routing algorithm applies an iterative function to select the optimal transportation mode/route through the network junctions along a given path. In general, multimodal trips are modelled in two stages. The first stage encompasses building a generic representation of each physical network, corresponding to the different transportation modes used. In the second stage, a routing algorithm is developed to estimate optimal paths across the defined multimodal network. To better capture the stochastic behaviour of transportation networks a traffic condition prediction methodology is proposed that uses changes in traffic speed as the traffic condition indicator to predict congestion levels in ports or other waterways. The procedure is then summarized in a flowchart and is followed by an example to demonstrate the application of the proposed methodology.

When about this algorithm application to multimodal transport, in [40] the author D. Ge has made a case study including the Japanese and Chinese ports and cities in safest and shortest path. There are many modes of transportation between cities, so the three most appropriate were taken in consideration, the road – highway, the railway and maritime transportation – waterway. In order to analyse and describe the problem more intuitively, a transportation network diagram of the possible transportation path of the scheme is constructed, which comprehended cities from Osaka, Japan to Chengdu, China.

It is important to mention that the vast majority of research about route optimization relies on a statistical basis gained from AIS (Automatic Identification System) data sources. Therefore, in the paper made by the authors Russel, Tijan et al. [41], a comprehensive literature review is done on the use of data obtained from the AIS, with an emphasis on vessel route prediction and seaport operations. This is very important because the AIS provide static (MMSI, IMO numbers, Name and Call Sign, length, beam and type of the ship, location of position fixing antenna), dynamic (Ship's position with accuracy indication, position time stamp, course and speed over ground (COG and SOG), heading, navigation status and rate of turn (ROT)), vessel related information (Ship's draught, type of hazardous cargo, destination, Expected Time of Arrival (ETA) and route plan) and short safety related messages. AIS is mainly used to locate the position of nearby vessels via GPS for collision avoidance. The AIS prevents collisions, helps ships chart and alter their routes whenever and wherever necessary. Following the recent developments, and some kind of AIS evolution, VHF Data Exchange System (VDES) is a communications system encompassing different subsystems of communications, one of them being the AIS. In that sense, the core element of VDES are new techniques providing higher data rates than those used for the AIS. It means that the VDES could have a significant positive impact on the provision of maritime information services, such as maritime safety information, general data communications at high data rates, locating, vessel traffic management, satellite communications, etc. using the AIS data there have been proposed a method that combines the semantic routes and the graph theory to address the extraction and expression of maritime traffic routes. The semantic approach is enhanced through the implementation with large amounts of AIS data. A good prediction of upcoming and unforeseen events can be of great assistance to the manoeuvring of the ship. Navigation in port areas and narrow passages is more likely to cause ship accidents. Numerous assistance systems exist, such as GPS, radar, digital maps, and other systems that provide information about the environment [41].

5. METEOROLOGICAL TRAFFIC-BASED SAFEST SHORTES PATH

5.1 Problem definitions and variables

The meteorological traffic-based safest shortest path is a modification of the shortest path algorithm which includes additional information from weather and traffic conditions to increase navigation safety. In the context of CRISIS project, it was put a major focus on sustainability, hence the main aim of such a problem formulation is to minimize environmental impact of navigation.

To simplify mathematical aspects, a navigation plan is defined as the result of a navigation request given a couple of points on a map and a given time. This definition is meant to highlight the static nature of the results, which are not updating in real time. However, fixed results do not limit the number of planning that could be requested, hence obtaining updated results whenever necessary.

The following variables were conceptually taken into account:

- **Sea/Land Map (Static):** the first variable to consider is the space of navigation: a sea/land map contains information about the exploration space.
- **Weather Conditions (Gathered Real Time)**: being in a marine environment, weather conditions affect navigation in several ways. For example, weather variables that could be considered are wind direction, wind intensity, air visibility, precipitation intensity, marine currents and waves. These weather variables are represented as a 4-dimensional tensor, containing spatial, temporal and "channel" information. Each channel represents a weather variable. For project needs, the variables which are taken into account were the precipitation intensity as an indicator for the weather conditions and wind direction and intensity for computing.
- **Traffic Conditions (Gathered Real Time)**: Real Time traffic conditions are useful to gather insights about the number of vessels that are currently navigating in a specific maritime area. Being able to track real-time traffic helps avoiding accidents, which is one of the most common causes of environmental disasters.
- **Aggregated Traffic Conditions (Static)**: Density Maps provided by external sources were considered when formulating the problem. They were initially considered to discourage travels in usually congested areas, however first tests when computing paths led to unusual paths, with the chance of increasing navigation risks (i.e.: navigation too much under coasts). For this reason, this kind of information were excluded from the project.

- **Marine Protected Areas (Static)**: Information about marine protected areas were included in navigation path computing both for regulatory constraints and environmental safety. For this reason, marine protected areas were considered with their degree of protection, hence discouraging travels through and/or around those areas, whenever possible.

A vertex in a map is considered an area of the real-world planisphere, quantized into regions with a constant area. Let two adjacent points, or vertexes, (A, B) in a map; two. Let an edge E a virtual entity connecting two adjacent vertexes in a map. An edge E is assigned with a total weight which is function of the following variables, chosen among the above ones: **Navigability Cost** (n_c), **Protection Cost** (p_c) **Wind Direction** (w_d), **Wind Intensity** (w_i), **Precipitation Intensity** (p_i), Where:

- **Navigability Cost** is a binary variable indicating if a vertex is navigable (sea, corresponding to ε, where ε is a small value)
- **Protection Cost** is a real variable, $p_c \in [0,1]$ indicating if a vertex is covered by a marine protected area, considering protection level
- **Wind Direction** is a discrete integer variable $w_d \in N,\ 0 \leq w_d \leq 7,$ discretized in the eight main cardinal directions, indicating the direction from which the wind comes. Wind direction starts from 0, indicating wind coming from north, and proceeds in clockwise direction until 7.
- **Wind Intensity** is a discrete integer variable $w_i \in N,\ 0 \leq w_d \leq 12$, obtained converting wind speed information based on the Beaufort Wind Scale[35]
- **Precipitation Intensity** is a real variable, $p_i \in [0,100]$ indicating the heaviness of precipitation based on the scales provided by external services[36]

Then the function $W: R \rightarrow R$ is defined as $W\big(x_B, y_B, n_c, p_i, MPA(x_B, y_B, w_i, w_d, p_c)\big)$ where x_B, y_B are the map coordinates of the point that is going to be reached, while $MPA(x_B, y_B, w_i, w_d, p_c)$ is a recursive function that computes a penalty based on the reached new position, and all vertex protection costs that are involved on a path based on the wind direction and intensity. Further details will be provided in section related to development details

In the realm of algorithmic navigation, several methods offer distinct approaches to solving the shortest path problem and they were detailed in the previous section. A first comparison brought to the following comparison:

- **Dijkstra's Algorithm** is known to explore all possible paths from a starting point, gradually expanding outward to find the shortest route.
- **Bellman-Ford Algorithm**, though similar, accommodates negative edge weights, making it suitable for scenarios where negative-cost edges might exist.

[35] Beaufort wind scale is available here https://www.rmets.org/metmatters/beaufort-wind-scale

[36] https://www.eoas.ubc.ca/courses/atsc201/A201Resources/RadarStormInterpTutorial/RadarReflectInterp.html

- **A* Algorithm** is renowned for its efficiency, but incorporates heuristics to guide the search, swiftly homing in on the optimal path with informed decision-making.
- **Genetic Algorithms**, iteratively refines solutions through selection, crossover, and mutation, trading off precision for adaptability.

While Dijkstra and Bellman-Ford ensure accuracy, A* balances efficiency and optimality, and Genetic Algorithms offer versatility in dynamic environments, each algorithm caters to distinct requirements, offering a rich array of tools for solving the shortest path problem.
Since the main focus is to preserve the environment and given the small area of interest, the first choice fell on accurate algorithms such as Dijkstra and Bellman-Ford. Moreover, given the mathematical formulation, negative edge weights are not allowed, so that **Dijkstra algorithm** was the most suitable choice.

5.2 Some examples: SEACONDITIONS and VISIR

The first end-user-oriented service to be developed is through TESSA (Development of Technology for Sea Situational Awareness), an industrial research project funded by the Italian Government. It was the platform SeaConditions, which actually provides ocean and weather forecasts, remote sensing data, and bathymetry for the Mediterranean Sea, both for PC-based and mobile channels. This platform was developed by Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC) in Lecce, Italy. The high level of customization possible with the MySeaConditions component is a response to the very specific needs of some of the users, such as repeated bulletins in a specific location and only for selected variables (e.g. waves, wind, water temperature). As described in [42], SeaConditions[37] was designed using a user-centred approach, in the field of weather services support, SeaConditions brings together four different types of Sea situational awareness (SSA) information:

(1) meteorological forecasts,

(2) state of the art marine forecasts,

(3) remote sensing observations and

(4) bathymetry.

The SeaConditions platform performs several procedures within its operational functioning:

- Firstly, it makes data acquisition of generic forecast products from Copernicus Marine Environment Monitoring Service (CMEMS)[38], from national Institute for Geophysics and Volcanology (INGV) for the

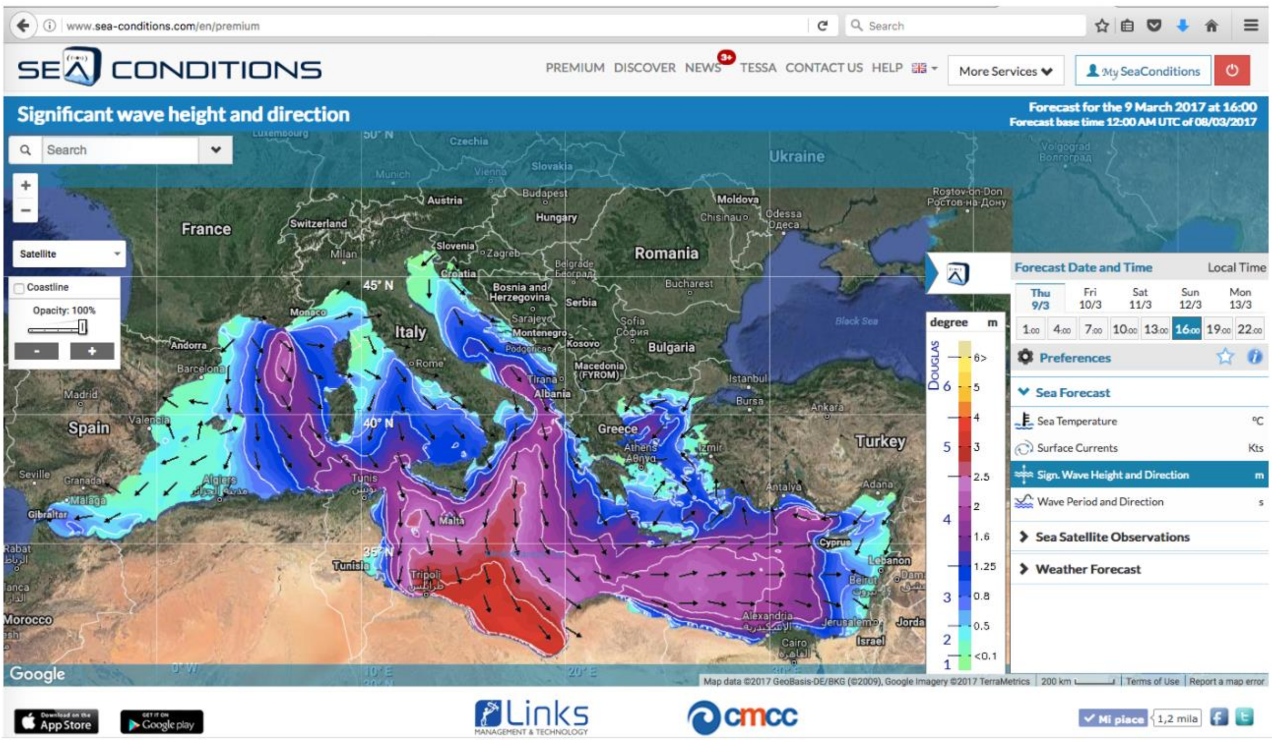
[37] The web application is available at www.sea-conditions.com and is accessible and compatible with present-day browsers

[38] https://marine.copernicus.eu/

oceanographic forecasts[39] and from CNMCA (Centro Nazionale di Meteorologiae Climatologia Aeronautica) of the Italian Met-Office(Aeronautica Militare) for the meteorological forecasts.

- Secondly, it produces the sub regional model forecasts, available for the Adriatic Sea Forecasting System (AFS) made by Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC).
- post-processing by the CMCC of the products provided by CMEMS, AFS and TSCFS
- map rendering by Links S.p.A. performed on the dedicated SSA platform generating information (e.g. maps and graphs) to the end-user.
- the service is provided to different end-user applications in a multi-channel mode (web and mobile, such as tablet and smartphone).

The SeaConditions have several oceanographic and hydrodynamic model products included in the application, due to track the ocean streams, currents, temperatures, and waves, counting their height, direction, and mean period for the Mediterranean, Tyrrhenian, and Adriatic Seas. These models comprise (NEMO-OPA)version 3.4, and WaveWatch-III (WW3) model, Adriatic Forecasting System (AFS) based on Princeton Ocean Model (POM), and TSCFS is the evolution and extension of the Sicily Channel Regional Model that represents a new implementation of the Princeton Ocean Model for the forecast of the 3-D ocean hydrology (temperature, salinity) and circulation in the central Mediterranean basin. All essential features of SeaConditions web application are shown on Figure 20.



---

39 https://www.ingv.it/

Figure 20 - SeaConditions web application shows a significant wave height and direction map.

(Source SeaConditions Website)

Having in mind the scope of services it provides, the SeaConditions is dedicated to the general public who wishes to know the meteorological and oceanographic conditions at sea. It provides a unique point of access to oceanographic and weather forecasts for the entire Mediterranean Sea. The portal of SeaConditions gives the insight of forecasts for surface temperature and currents, significant wave height and direction and wave period and direction, air temperature, mean sea level pressure, total precipitation, total cloud coverage and winds, chlorophyll concentration, water transparency, and among all these, the most important are bathymetry and awash rocks.

Routing of vessels is of essential importance for several maritime navigation aspects. Especially the routing of sailing boats has many positive effects on marine environment and fuel cost saving and optimization. Therefore, according the research conducted in [43], the introduction of sailboat into ship routing system VISIR (*discovering Safe and efficient Routes*) could significantly contribute to overall maritime and operational safety, protection of environment and navigation optimization. For this purpose a model for computing least-time routes for sailing ships in dynamic environment has been made, relying on exact optimization algorithm, with computing the manoeuvres for various sea conditions situations, whether upwind or downwind sailing. This model as variables has included sea currents, wind forecast, sailboat classes, oceanographic flows, wave models. The algorithm proposed in the [43] is based on local optimization of sailboat course, constrained with the width of route corridor in order to deal with sudden changes of wind and currents. In this case, the simplex algorithm is used, which requires the user to set up the navigation waypoints on the route. The scope of the algorithm is further enlarged by adding the position of departure and an arrival mark. Moreover, the algorithm takes in consideration the existence of obstacles near the coasts and a limiter Under Keel Clearance (UKC) in shallow waters, but the broader ingestion of data about winds and sea currents are also considered to be enhanced. These requirements indicate on the need to employ a graph-search algorithm. On the direct algorithm developed in this research the nodes are on regular grid in latitude / longitude coordinates with spacing 1/60°, or about 1 Nautical Mile along the meridional direction. Thus, this algorithm is used for making the optimal routes, which means that these paths on the graph minimize or maximize the sum of edge weight along the route, and therefore, to determine the optimal route the both exact and heuristics-based models are used, among which the Dijkstra algorithm provides optimality in routes computing.

In last decade, the attempt to build a fully open ship routing model is personalized through VISIR (*discoVerIng Safe and effIcient Routes*) platform that has the capacity to provide optimized navigation route to vessel management divisions by integrating the numerical optimization methods, hydrodynamic effects considerations, various approximations, weather forecasts etc. This includes a copylefted (GPL v.3) free and open-source code, available at www.visir-model.net. In general, the VISIR aims at optimizing nautical routes in the presence of both static and dynamic constraints arising from the ocean topology and environmental conditions, using the Wave Watch-III model for wave forecasts, as well. Motor vessels with displacement hulls are considered in the first version of the model (VISIR-I). The optimization algorithm is based on a graph search method by Dijkstra. The graph itself is represented as a list of edges and, for enhancing computational performance, the algorithm uses a “forward star” data structure. According to the paper [44], the VISIR is suited for use in the presence of complex topology: routes can be optimized even in sea domains containing peninsulas, islands, and archipelagos. Besides a shoreline and a bathymetry database, the model needs an input forecast or analysis fields of sea state (significant wave height, wave period, and direction). VISIR model was designed to ingest operational meteo-oceanographic forecasts and eventually become the engine of a new operational Decision Support System. VISIR-I is coded in Matlab®. The code of VISIR was designed and implemented with an effort to follow the guidelines from software engineering manuals and collections of best practices in scientific programming. In VISIR we considered and implemented the following principles:

- Modularity,
- Semantic consistency,
- Checks, tracking, and regression tests,
- Profiling, portability and documentation.

VISIR computing time depends on route length, through the graph size *N*, as shown in Figure 21. The main contributors to such time expenditure are the graph edge preparation and the two calls (geodetic and optimal route) to the shortest path routine. Furthermore, the computational cost for edge preparation is dependent on actual sea conditions: the rougher the sea, the lower the sustained ship speed, and consequently the longer the route duration.

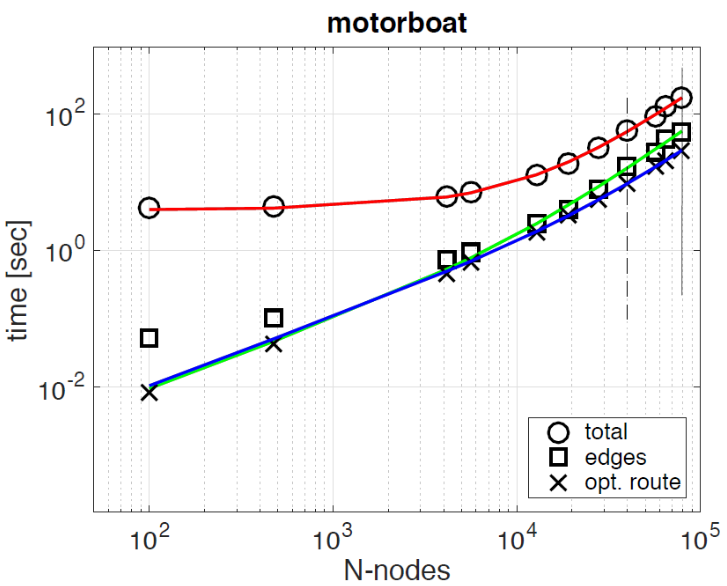


Figure 21 - VISIR code performance as function of the number N *of graph grid points within the selected bounding box*

(Source [44])

The operational availability of high spatial and temporal resolution forecasts, for weather, sea state, and oceanographic variables paves the way to a realm of downstream services, which are increasingly closer to end-user needs. Such services may support the decision-making process in critical situations where knowledge of the present and predicted environmental state is key to avoiding casualties or to making savings in terms of time, economic cost, or environmental impact. The model is comprised of three components: a route optimization algorithm, a mechanical model of the ship, and a processor of the environmental fields. The optimization algorithm is based on a graph-search method with time-dependent edge weights. The algorithm is also able to compute a voluntary ship speed reduction.

In VISIR, the choice of vessel parameters, the variety of possible sea states, and the freedom to select departure and arrival from any two points in the Mediterranean Sea give rise to a considerable number of route features. Finally, the paper [45] generated a few prototypical situations, demonstrating the features of the developed model together with related components. As an example provided within the case study is an optimized route in Mediterranean Sea is given for the area from Tunisia to South Italy.

The VISIR model has been developed in order to provide users with information on Sea Currents and Waves for Optimal Route Planning, and represents one the most important operational marine-weather routing system for the Mediterranean Sea, available at www.visir-nav.com. Its algorithm for computing the shortest routes has been validated versus analytical results in case of static wave fields. VISIR employs sea-state information also for performing a few checks of vessel intact stability, namely related to: parametric roll, pure loss of stability, and surf riding/broaching-to. The algorithm then constructs the optimal route by ensuring that vessel intact stability is always satisfied. In the VISIR version described in [45], a graph mesh with a 1/60 degree spacing (i.e., about 1 M in the meridional direction) and an angular resolution of about 27° were considered. For this reason, the angular resolution of VISIR was improved by considering edges between all nodes up to the fourth and not just the second order of neighbours of a squared mesh. The developments of VISIR require hydrodynamic and sea-state forecast fields in input. They are both obtained from the CMEMS operational system, marine.copernicus.eu.

Another important feature of decision support tools for the safest and shortest route that have a significant environmentally-friendly characteristic is the GUTTA-VISIR platform that runs as a service for operationally providing least-CO2 ferry routes, as described in [46]. It combines numerical meteo-oceanographic forecasts with both the ship route optimization model VISIR and a dedicated environment for operational production. This platform is launched and function in continual operation from 2021, finally integrated by CMCC. Both the CO2 and the Carbon Intensity Indicator (CII) savings resulting from route optimization are provided to the end users, which is available as a web application on the link www.gutta-visir.eu. The usage of this platform is of essential importance, since in the meantime, the European Union (EU) has made independent steps to accelerate maritime decarbonization, and this is a reason for the development and implementation of such a platform which will strongly contribute to goals of pollution reduction by optimizing the vessel voyage routes. Thus, saving both fuel consumption and GHG emissions will be increasingly important. Therefore, the CMCC has been developing the VISIR open-source model[40] for weather routing for the past ten years. In more details, the version recently used, VISIR-2, is a Python software meant for computing optimal ship routes in the presence of dynamic marine weather fields, which is inspired and validated after its predecessor, the Matlab-coded VISIR-1 model. In general, the model consists of four main components:

- Vessel response model,
- Environmental fields,
- Path planning component

[40] https://www.visir-model.net/

- Visualisation.

As a result of such development, there has been created a web application GUTTA-VISIR, as shown in the following figure, with all necessary tools and services available on a multi-layered application interface, such as visualization of entered commands, and information about departure date and time, ferry engine load factor, as well as both the wave and current forecasts.

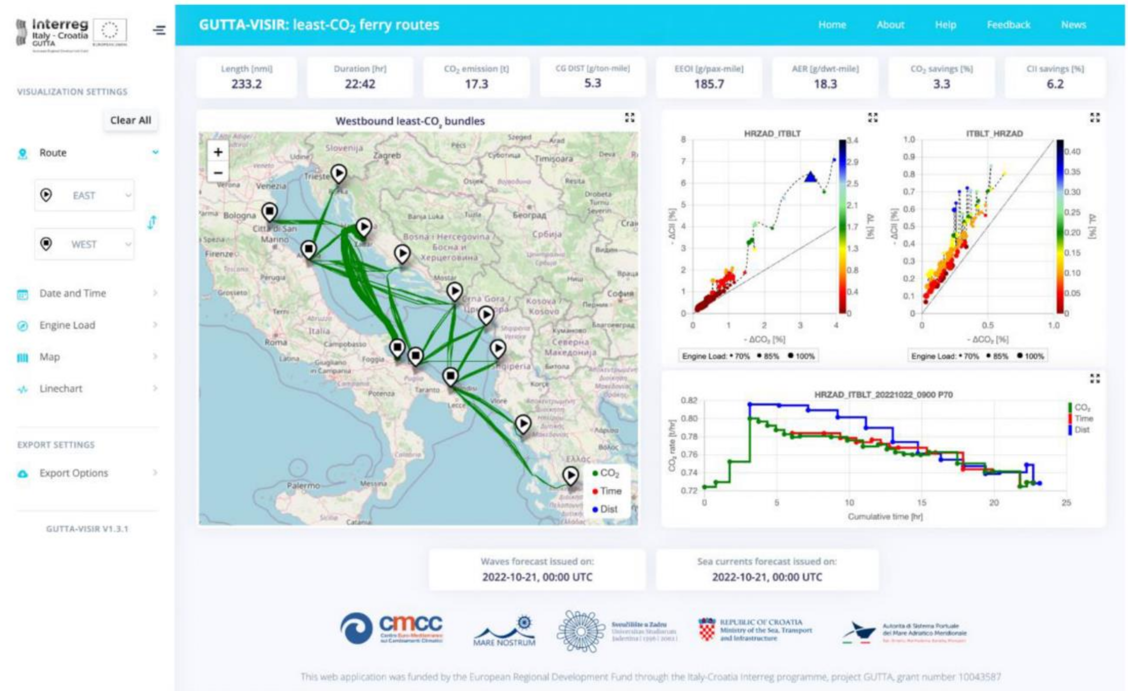


Figure 22 - GUTTA-VISIR web app

(Source [46])

Moreover, the routes can be explored not only in their geographical aspects but also through some key metrics relevant to decarbonization. Additionally, the body of the GUTTA-VISIR web applications includes a section with a scatter plot of CII vs. CO2 savings. This plot conveys also synthetic information on how effective diversions are in reducing the carbon footprint of routes. It includes a section ("line chart") with information along a specific route, useful to compare either the CO2 or the CII timeline of the CO2-optimal vs. the fastest and the shortest route between the same ports, as well. To this end, all optimal routes so far produced by the operating system were analysed, as approved by [46]. Subsequently, the CO2 savings were assessed in relation to both dates of navigation and marine conditions and sea domain. Finally, we assessed the CII savings computed by GUTTA-VISIR during the first eleven months of operation. As shown in [47], CII savings are given by the sum of the CO2 savings and the optimal route's relative lengthening with respect to the geodetic one.

Following the recent developments of VISIR platform, in the paper [48], the optimal ship tracks computed via the VISIR model are compared to tracks recorded by the Automatic Identification System (AIS). In this research, VISIR is fed by wave analysis fields from the Copernicus Marine Environment Monitoring Service (CMEMS). In order to reproduce vessel speed loss in waves, a new methodology is developed, where kinematic information from AIS is fashioned with wave information from CMEMS. In that sense, a contribution to this topic is reflected through an inter-comparison exercise between reported vessel tracks as collected through the Automatic Identification System (AIS) and tracks planned through the ship route optimization model VISIR. The methodology for evaluation of the mentioned experiment consists of three phases of examination: extraction of AIS tracks from reported raw data, the computation of optimal tracks through VISIR, the computation of the vessel speed loss in waves out of AIS kinematic information, VISIR vessel performance model, and sea state analysis fields, in order to compare AIS and VISIR tracks.

5.3 Dijkstra Safest Shortest Path implementation

This section is dedicated to some implementation details provided from the safest shortest path problem source code. First of all, one of the most important work is the data structure layering which is based on two static layers (maps) which were precisely gathered, cut on the area of interest and pre-processed to be mapped with the variables explained in the mathematical formulation section:

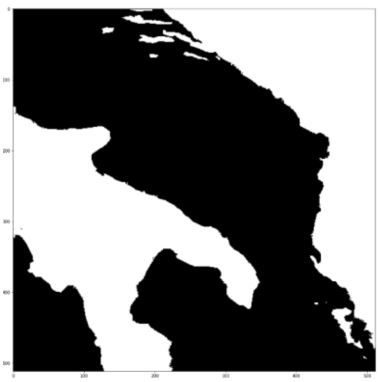


Figure 23: Pre-processed 512x512 Map. Black areas are the navigable ones, white areas are not navigable

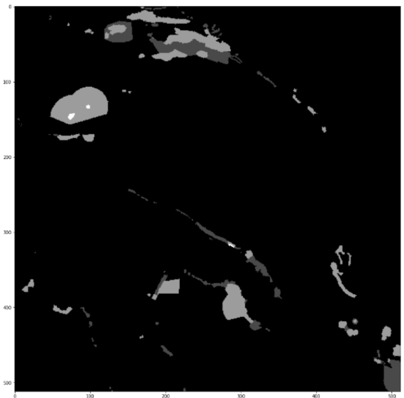


Figure 24: Pre-processed 512x512 map of the Marine protected areas, scales of grey. Lighter areas are more protected

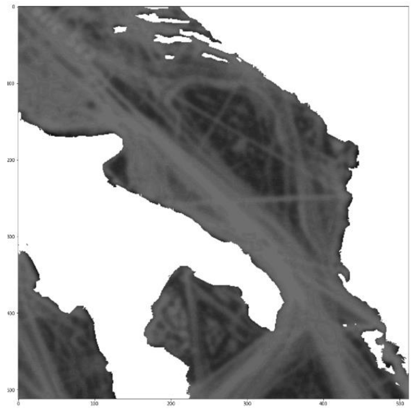


Figure 25: Overlapped pre-processed 512x512 map for navigable areas with traffic density information (2022)

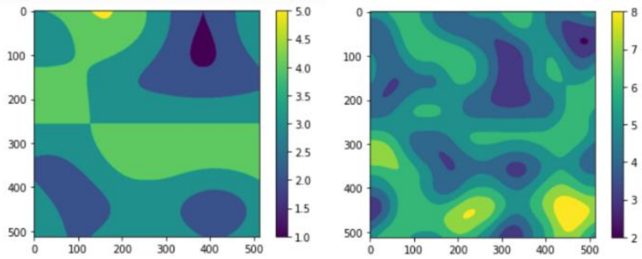


Figure 26: 512x512 Maps for wind directions (left) and intensity (right) from weather services

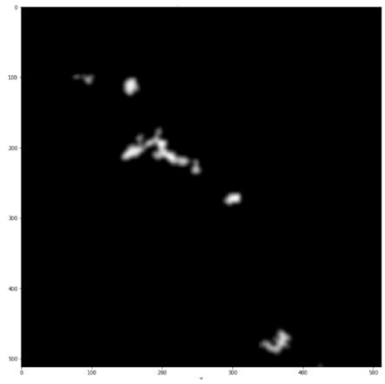


Figure 27: 512x512 Weather map for precipitation intensity

The above shown maps are mixed results from static pre-processing (Navigable map, Static traffic information, Marine protected areas) and information gathered from external services (wind variables and precipitation information). All these maps, as well as the input information coming from the CRISIS platform, are fed to the Safest Shortest Path code to obtain the resulting path with annotations.

```
class SPPQueueThread(Thread):

    def __init__(self, queue, broker, port, topic):
        Thread.__init__(self)
        self.queue = queue
        self.broker = broker
        self.port = port
        self.topic = topic


    def run(self):

        receiveSPPMessage(self.broker, self.port, self.topic)

        while True:

            try:
                message = self.queue.get()
                if message is None:
                    continue

                input_json = decodeMessage(message)
                data = input_json
                Log(data)
                result = load_json_and_run(data)
                Log(result)
                send_message(self.broker, self.port, response_topic, result)
            except Exception as e:
                Log("An error occurred while calling shortest safe path planning -> "+ str(e) + "\n")
                continue
```

Figure 28: App manager - Inject Backend Request

```python
def load_json_and_run(inp_json, matrix_source='JSON'):


    ship_id = inp_json.get("SHIP_ID", "")
    ship_name = inp_json.get("SHIP_NAME", "Ship")
    timestamp = inp_json.get("TIMESTAMP", datetime.now())
    wharf_id = inp_json.get("WHARF_ID", "")
    weather_matrix = np.asarray(inp_json.get("WEATHER_MATRIX", [0])[-1].get("weatherMatrix",[[0],[0]]))
    start = (start_lat, start_lon)
    start= (42.00, 14.95)
    end = (end_lat, end_lon)

    if weather_matrix.shape != (512,512):
        return "An error occurred while checking matrix dimension"

    path, annotations = run(weather_matrix, start, end)


    path_sampled = path[::10]
    path_sampled.append(path[-1])
    path_coords = [convert_pixel_to_lat_lon(x) for x in path_sampled]

    resp = build_response_json(path_sampled, path_coords, ship_id, ship_name, timestamp,\
                               wharf_id, start_lat, start_lon, end_lat, end_lon, annotations)

    return resp
```

Figure 29: Shortest Safe Path Entry point function

```python
def run(weather_matrix, starting_points, ending_points):


    # Marine Protected Areas Map
    MPA = plt.imread("./Map_Def_Areas_BW2.png")

    #Wind Map
    intensity_map, direction_map = generate_separate_wind_intensity_and_direction_maps(weather_matrix)

    # Base Map with land and sea
    base = plt.imread("Map_BW_Clean_Def.png")
    base_2 = plt.imread("Map_BW_Clean_Def.png")

    smoothed_weight_matrix = gaussian_filter(weather_matrix, sigma=3)
    weight_matrix = np.asarray(smoothed_weight_matrix, dtype="int")
    normalized_weight_matrix = weight_matrix / 100

    # Djkstra Matrix for wind, includes MPA and weather
    total_matrix = np.where(base <= normalized_weight_matrix, normalized_weight_matrix, base).clip(0,1)
    total_matrix = np.where(total_matrix <= MPA, MPA, total_matrix).clip(0,1)*20
    total_matrix = gaussian_filter(total_matrix, sigma=1)
    total_matrix = total_matrix + np.full(total_matrix.shape, 1)
    djkstra_matrix = np.where(total_matrix<np.max(total_matrix)*0.999, total_matrix, total_matrix*1000000000)

    # Djkstra Matrix only land for shortest path
    tot_matrix = base_2.clip(0,1)*20
    tot_matrix = gaussian_filter(tot_matrix, sigma=3)
    tot_matrix = tot_matrix + np.full(tot_matrix.shape, 1)
    djkstra_matrix_2 = np.where(tot_matrix<np.max(tot_matrix)*0.999, tot_matrix, tot_matrix*1000000000)

    start_x, start_y = convert_latitude_longitude_to_pixel(starting_points)
    end_x, end_y = convert_latitude_longitude_to_pixel(ending_points)


    total_cost, path = dijkstra_wind(djkstra_matrix, (start_x, start_y), (end_x, end_y), MPA, intensity_map, direction_map)
    total_cost_2, path_2 = dijkstra2(djkstra_matrix_2, (start_x, start_y), (end_x, end_y))

    sust_notes = computeSustainabilityIndices(djkstra_matrix_2, djkstra_matrix, path_2, \
                                              path, intensity_map, direction_map, MPA)

    print(f"Start Point: ({start_x}, {start_y})")
    print(f"End Point: ({end_x}, {end_y})")
    print(f"Total Cost: {total_cost}")

    annotations, _ = cross_areas_detection(path, normalized_weight_matrix, MPA)
    annotations_alt, MPA_edges_coord = cross_areas_detection(path_2, normalized_weight_matrix, MPA)

    annotations_wind = []
    for edge in MPA_edges_coord:
        annotations_wind.append(wind_info_by_coords(direction_map, intensity_map, edge))

    annotations = sust_notes + annotations + annotations_wind


    # Plot Map
    map_base = plt.imread("Map With Marine Areas.png")
    plot_weight_matrix(map_base, path, (start_x, start_y), (end_x, end_y))
    plot_weight_matrix(total_matrix, path, (start_x, start_y), (end_x, end_y))
    plot_weight_matrix(normalized_weight_matrix, path, (start_x, start_y), (end_x, end_y))

    map_base = plt.imread("Map With Marine Areas.png")
    plot_weight_matrix(map_base, path_2, (start_x, start_y), (end_x, end_y))


    return path, annotations
```

Figure 30: Shortest Safest Path execution code

```python
def dijkstra_wind(matrix, start, end, MPA, intensity_map, direction_map):
    rows, cols = matrix.shape
    distance = np.full((rows, cols), float('inf'))
    prev = np.full(matrix.shape, None, dtype=object)
    visited = np.zeros((rows, cols), dtype=bool)
    queue = []

    start_x, start_y = start
    end_x, end_y = end

    distance[start_x, start_y] = matrix[start_x, start_y]
    heapq.heappush(queue, (distance[start_x, start_y], (start_x, start_y)))

    # Define neighbors including diagonal ones
    neighbors = [
        (-1, 0), (1, 0), (0, -1), (0, 1),
        (-1, -1), (-1, 1), (1, -1), (1, 1)
    ]

    while queue:
        curr_cost, (curr_x, curr_y) = heapq.heappop(queue)

        if visited[curr_x, curr_y]:
            continue

        visited[curr_x, curr_y] = True

        if (curr_x, curr_y) == (end_x, end_y):
            break

        for dx, dy in neighbors:
            nx, ny = curr_x + dx, curr_y + dy

            if 0 <= nx < rows and 0 <= ny < cols:
                cost = curr_cost + matrix[nx, ny]

                if dx != 0 and dy != 0:  # Diagonal movement
                    cost = curr_cost + np.sqrt(2) * matrix[nx, ny]

                cost += compute_MPA_wind(intensity_map, direction_map, MPA, (nx, ny))

                if cost < distance[nx, ny]:
                    distance[nx, ny] = cost
                    prev[nx, ny] = (curr_x, curr_y)
                    heapq.heappush(queue, (cost, (nx, ny)))
    path = []
    x, y = end_x, end_y
    while (x, y) != (start_x, start_y):
        path.append((x, y))
        x, y = prev[x, y]
    path.append((start_x, start_y))

    return distance[end_x, end_y], path[::-1]  # Return total cost and reversed path
```

Figure 31: 8-neighbors matrix Dijkstra algorithm implementation

```python
def compute_MPA_wind(intensity_wind, direction_wind, MPA, cur_point):

    x, y = cur_point
    n_steps = direction_wind[x, y]
    cost = 0

    for i in range(0, n_steps*5):
        if x == 512 or y==512 or x==0 or y==0: break
        dx, dy = direction_vectors[direction_wind[x, y]]
        cost += MPA[x, y]*1000
        x, y = x+dx, y+dy

    return cost
```

Figure 32: Compute wind based on marine protected areas

```python
def cross_areas_detection(path, weather, MPA):

    annotations = []
    path = np.array(path)
    MPA_number = 0
    weather_number = 0
    MPA_edges = []
    weather_edges = []

    MPA_crossed = np.array([MPA[lat, lon] for lat, lon in path])
    weather_crossed = np.array([weather[lat, lon] for lat, lon in path])

    # Indexes to browse path, useful to check how many areas
    MPA_indexes = np.argwhere(MPA_crossed > 0)
    weather_indexes = np.argwhere(weather_crossed > 0.5)

    # Section to individuate indexes with marine protected areas / bad weather areas crossed
    if MPA_indexes.shape[0] > 0:
        MPA_edges, MPA_number = count_areas(MPA_indexes)

    if weather_indexes.shape[0] > 0:
        weather_edges, weather_number = count_areas(weather_indexes)

    MPA_edges_pixels = [[path[s], path[e]] for s, e in MPA_edges]
    MPA_edges_coords = [[convert_pixel_to_lat_lon(s), convert_pixel_to_lat_lon(e)] for s, e in MPA_edges_pixels]

    weather_edges_pixels = [[path[s], path[e]] for s, e in weather_edges]
    weather_edges_coords = [[convert_pixel_to_lat_lon(s), convert_pixel_to_lat_lon(e)] for s, e in weather_edges_pixels]

    # Pixel-related paths
    MPA_path = path[MPA_indexes]
    weather_path = path[weather_indexes]



    message = f"{MPA_number} marine protected area crossed"
    annotations.append(message)

    for start, end in MPA_edges_coords:
        message = f"Marine protected area starts at: {start} and ends at: {end}"
        annotations.append(message)


    message = f"{weather_number} bad weather areas encountered in path"
    annotations.append(message)

    for start, end in weather_edges_coords:
        message = f"Bad weather starts at: {start} and ends at: {end}"
        annotations.append(message)

    return annotations, MPA_edges_coords
```

Figure 33: Dangerous area crossing detection snippet - Used in annotations

6. BIBLIOGRAPHY

[1] CRISIS project Consortium, «CRISIS Application Form,» INTERREG IPA CBC ITALY–ALBANIA–MONTENEGRO PROGRAMME, 2ND CALL FOR PROJECTS IPA II CBC ITALY-ALBANIA-MONTENEGRO - TARGETED, Bari, Italy, 2022.

[2] G. J. Edgar, G. R. Russ e R. C. Babcock, Marine Ecology - Chapter 19 Marine protected areas, Oxford University Press, 2007.

[3] European Environment Agency (EEA), «Marine protected areas conserve life,» 2018.

[4] Marine Conservation Institute, «Global Marine Fishing Protection,» 2023.

[5] M. C. de Francesco e F. Iannotta, «Riserva Naturale Regionale "Marina di Vasto" - Disciplinare per la riqualificazione ambientale degli accessi all'area idonea alla balneazione pulizia dell'arenile, delle aree in concessione e degli ambienti dunali,» Centro Studi D.E.M.E.T.R.A.e Università degli Studi del Molise, 2018.

[6] Consorzio Interuniversitario per le Scienze del Mare (CoNISMa), «Area Marina Protetta "Isole Tremiti" - Cartografia degli habitat Bentonici,» Aree Speciali Protette di Importanza Mediterranea (ASPIM), 2012.

[7] Ente Parco Nazionale del Gargano, «AMP Isole Tremiti,» Ministero dell'Ambiente e della Sicurezza Energetica, 2023.

[8] ISPRA, «Repertorio nazionale degli interventi di ripristino - 6e - Puglia - Sistemazioni idraulico-forestali a Marina di Lesina,» 2013.

[9] Global Petroleum Ltd., «Allegato 4: Descrizione dei siti Rete Natura 2000 - Istanza di Permesso di Ricerca di Idrocarburi a Mare,» 2014.

[10] Ministero dell'Ambiente e della Tutela del Territorio e del Mare, «Approvazione del regolamento di esecuzione ed organizzazione dell'area marina protetta "Torre Guaceto",» GAZZETTA UFFICIALE DELLA REPUBBLICA ITALIANA, 2009.

[11] Regione Puglia, Istituzione del Parco naturale regionale 'Salina di Punta della Contessa'", Bollettino Ufficiale della Regione Puglia n.164 del 30 dicembre 2002, 2002.

[12] Regione Puglia, SIC Torre Veneri; IT9150025; Regolamento.

[13] the Public Enterprise for Coastal Zone Management of Montenegro, *INFOMATION about permited and prohibited activities in Nature Parks PLATAMUNI, KATIČ and STARI ULCINJ,* Budva: the Public Enterprise for Coastal Zone Management of Montenegro, 2023.

[14] INTERNATIONAL MARITIME ORGANIZATION, «Fourth IMO GHG Study 2020,» IMO, London, 2021.

[15] A. Idri, M. Oukarfi, A. Boulmakoul, K. Zeitouni, A. Masri, «A new time-dependent shortest path algorithm for multimodal transportation network,» The 8th International Conference on Ambient Systems, Networks and Technologies (ANT 2017) - Procedia Computer Science 109C, pp. 692-697,, 2017.

[16] Inan, T., & Baba, A. F. , «Finding and Comparing Shortest Path Solutions by Using Various Methods on a Detailed Network of the Aegean Sea,» *Global Journal of Computer Sciences: Theory and Research, 8(3), 96–110. (2018). https://doi.org/10.18844/gjcs.v8i3.3738.*

[17] P. Silveira, A. P. Teixeira & C. Guedes Soares, «AIS Based Shipping Routes Using the Dijkstra Algorithm,» *the International Journal on Marine Navigation and Safety of Sea Transportation,* n. DOI: 10.12716/1001.13.03.11, September 2019.

[18] Wang, N.; Sun, Z.; Yin, J.; Zou, Z.; Su, S.-F. , «Fuzzy unknown observer-based robust adaptive path following control of underactuated surface vehicles subject to multiple unknowns.,» *Ocean Eng. 2019, 176, 57–64..*

[19] Liu, Y.C.; Bucknall, R., « Path planning algorithm for unmanned surface vehicle formations in a practical maritime environment.,» *Ocean Eng. 2015, 97, 126–144..*

[20] Cheng, T.; Utne, I.B.; Wu, B.;Wu, Q. , «A novel system-theoretic approach for human-system collaboration safety: Case studies on two degrees of autonomy for autonomous ships.,» *Reliab. Eng. Syst. Saf. 2023, 237, 109388..*

[21] Zhibo He, Chenguang Liu, Xiumin Chu, Rudy R. Negenborn, Qing Wu,, «Dynamic anti-collision A-star algorithm for multi-ship encounter situations,,» *Applied Ocean Research,,* vol. 118, n. https://doi.org/10.1016/j.apor.2021.102995., pp. ISSN 0141-1187,, 2022.

[22] Rong Zhen , Qiyong Gu , Ziqiang Shi, Yongfeng Suo, «An Improved A-Star Ship Path-Planning Algorithm Considering Current, Water Depth, and Traffic Separation Rules,» *J. Mar. Sci. Eng. 2023, 11, 1439.,* n. https://doi.org/10.3390/jmse11071439.

[23] Ayawli, B.B.K.; Chellali, R.; Appiah, A.Y.; Kyeremeh, F. , «An Overview of Nature-Inspired, Conventional, and Hybrid Methods of Autonomous Vehicle Path Planning.,» *J. Adv. Transp. 2018, 8269698.*

[24] Chenguang Liu, Qingzhou Mao, Xiumin Chu, Shuo Xie, «An Improved A-Star Algorithm Considering Water Current, Traffic Separation and Berthing for Vessel Path Planning,» *Appl. Sci. 2019, 9(6), 1057; https://doi.org/10.3390/app9061057.*

[25] Ramesh lempepatil, Vishwas V Rudraswamymath, «Advanced study of Shortest Route Problem and its applications- bellman – ford algorithm,» *ISSN: 2455-2631 June 2023 IJSDR | Volume 8 Issue 6.*

[26] PAUL WILSON, B.Eng., «Accurate Prediction of Maritime Trajectories From Historical AIS Data Using Grid-Based Methods,» *Master Thesis - McMaster University, Hamilton, Ontario, Canada,* 2017.

[27] Cherkassky, B.V., Goldberg, A.V. & Radzik, T., «Shortest paths algorithms: Theory and experimental evaluation,» *Mathematical Programming 73, 129–174 (1996). https://doi.org/10.1007/BF02592101.*

[28] Timofeeva, O.; Sannikov, A.; Stepanenko, M.; Balashova, T. , «Modification of the Bellman–Ford Algorithm for Finding the Optimal Route in Multilayer Network Structures.,» *Computation 2023, 11, 74. https://doi.org/10.3390/computation11040074.*

[29] M.Wootters, «Shortest Path and Dynamic Programming Algorithms,» *CS161Lecture12,* n. http://web.stanford.edu/class/archive/cs/cs161/cs161.1176/Lectures/CS161Lecture12.pdf, 2017.

[30] Y. Lu, Sh. Wang,, «Optimization of Joint Decision of Transport Mode and Path in Multi-Mode Freight Transportation Network,» *Sensors, Vol. 22, p. 4887., https://doi.org/10.3390/s22134887,* 2022.

[31] J. Dibbelt, «Engineering Algorithms for Route Planning in Multimodal Transportation Networks,» PhD dissertation, Fakultät für Informatik des Karlsruher Instituts für Technologie (KIT), 2016..

[32] X. Zhou, J. Du, «Research on Optimization of Logistics Transportation Mode Based on Multimodal Transportation,» *3rd International Conference on Economic and Business Management (FEBM 2018), Advances in Economics, Business and Management Research, volume 56, 2018..*

[33] Y. Zhao, «Optimization of Multimodal Transportation Network Based on Improved Genetic Algorithm,» *2nd International Conference on Applied Mathematics, Modelling and Statistics Application (AMMSA 2018), Advances in Intelligent Systems Research, volume 143, 2018..*

[34] Y. Sun, M. Lang, D. Wang, «Optimization Models and Solution Algorithms for Freight Routing Planning Problem in the Multi-Modal Transportation Networks: A Review of the State-of-the-Art,» *The Open Civil Engineering Journal, , Vol. 9, pp. 714-723, 2015..*

[35] S. Okyere, J. Yang, Ch. Adams, «Optimizing the Sustainable Multimodal Freight Transport and Logistics System Based on the Genetic Algorithm,» *Sustainability, Vol. 14, p. 11577, 2022., https://doi.org/10.3390/su141811577.*

[36] Y. Lu, X. Pei, Ch. Zhang, H. Luo, B. Liu, Zh. Ma, «Design of Multimodal Transport Path Optimization Model and Dual Pheromone Hybrid Algorithm,» *Journal Européen des Systèmes Automatisés Vol. 52, No. 5, pp. 477-484, 2019..*

[37] Y. Zhou, Ch. Cao, Z. Feng, «Optimization of Multimodal Discrete Network Design Problems Based on Super Networks,» *Appl. Sci. 2021, 11, 10143. https://doi.org/10.3390/app112110143.*

[38] L. Liu, L. Meng, «Algorithms of Multi-Modal Route Planning Based on the Concept of Switch Point,» *Photogrammetrie, Fernerkundung, Geoinformation Vol. 5/2009, pp. 431–444, 2009..*

[39] B. Rouhieh, «Modeling And Optimizing Route Choice For Multimodal Transportation Networks,» *Ph.D. Dissertation, Concordia University, Montreal, Quebec, Canada, 2016..*

[40] D. Ge, «Optimal path selection of multimodal transport based on Ant Colony Algorithm,» *2021 2nd International Conference on Applied Physics and Computing (ICAPC 2021), Vol. 2083, No.032011, doi:10.1088/1742-6596/2083/3/032011.*

[41] E. Russell Montiel, R. Klunk, E. Tijan, M. Jović, «Using Automatic Identification System Data in Vessel Route Prediction and Seaport Operations,» *Pomorski zbornik 61 (2021), 45-56.*

[42] 8. G. Coppini, P. Marra, R. Lecci, N. Pinardi, S. Cretì, M. Scalas, L. Tedesco, A. D'Anca, L. Fazioli, A. Olita, G. Turrisi, C. Palazzo, G. Aloisio, S. Fiore, A. Bonaduce, Y. Kumkar, S. Ciliberti, I. Federico, G. Mannarini, P. Agostini, R. Bonarelli, S. M, «SeaConditions: a web and mobile service for safer professional and recreational activities in the Mediterranean Sea,» *Nat. Hazards Earth Syst. Sci., 17, 533–547, 2017, doi:10.5194/nhess-17-533-2017..*

[43] G. Mannarini, R. Lecci, G. Coppini, «Introducing sailboats into ship routing system VISIR,» *6th International Conference on Information, Intelligence, Systems and Applications (IISA), 2015., DOI: 10.1109/IISA.2015.7387962. .*

[44] G. Mannarini, N. Pinardi, G. Coppini, , «VISIR: A Free and Open-Source Model for Ship Route optimization,» *15th International Conference on Computer and IT Applications in the Maritime Industries, COMPIT'16, Lecce, 9-11 May 2016..*

[45] G. Mannarini, N. Pinardi, G. Coppini, P. Oddo, A. Iafrati , «VISIR-I: small vessels – least-time nautical routes using wave forecasts,» *Geosci. Model Dev., Vol. 9, pp.1597–1625, 2016..*

[46] G. Mannarini, L. Carelli, F. Viola, M. Hoxhaj, M. Scuro, S. Kyal, R. Lecci, G. Coppini, «The Gutta-Visir System for Operational CO2 Emission Savings from Ferries,» *Scaling Decarbonisation Solutions: Reducing Emissions by 2030, 2022..*

[47] G. Mannarini, L. Carelli, J. Orović, C.P. Martinkus, G. Coppini, «Towards Least-CO2 Ferry Routes in the Adriatic Sea,» *J. Mar. Sci. Eng., Vol. 9, p.115, 2021,. https://doi.org/10.3390/jmse9020115.*

[48] G. Mannarini, L. Carelli, D. Zissis, G. Spiliopoulos, K. Chatzikokolakis, «Preliminary Inter-comparison of AIS Data and Optimal Ship Tracks,» *the International Journal on Marine Navigation and Safety of Sea Transportation (TRANSNAV), Vol. 13, No. 1, 2.*

Contacts

LP Municipality of Molfetta
antonella.fatone@comune.molfetta.ba.it

PP2 FLAG Molise Costiero
info@flagmolise.it

OPŠTINA ULCINJ
KOMUNA E ULQINIT

PP3 Municipality of Ulcinj
kabinet@ul-gov.me

This project is co-financed by the European Union under the instrument for Pre-Accession Assistance (IPA II)

This document has been produced with the financial assistance of the Interreg IPA CBC Italy-Albania-Montenegro Programme. The contents of this document are the sole responsibility of Municipality of Molfetta, FLAG Molise Costiero and Municipality of Ulcinj and can under no circumstances be regarded as reflecting the position of the European Union and of the Interreg IPA CBC Italy-Albania-Montenegro Programme Authorities.