Ship routing in Particularly Sensitive Sea Areas

Angela Di Febbraro[a], Davide Giglio[a], Roberto Ronco[b,*]

[a] University of Genoa, Genoa, Italy
angela.difebbraro@unige.it, davide.giglio@unige.it
[b] Institute of Marine Engineering, National Research Council, Genoa, Italy
roberto.ronco@cnr.it
[*] Corresponding author

Extended abstract submitted for presentation at the Conference in Emerging Technologies in Transportation Systems (TRC-30)
September 02-03, 2024, Crete, Greece

April 29, 2024

Keywords: Maritime Transportation
Ship Routing
Particularly Sensitive Sea Areas
Mixed-integer Programming

1 Introduction and motivation

The problems related to ship routing have attracted the interest of many researchers for decades. The interest has always been renewed by both the changes in regulations and laws, and the technological advances.

The 1982 United Nations Convention on the Law of the Sea (UNCLOS) designated the International Maritime Organization (IMO) as the primary international authority for navigational safety, shipping traffic safety, and marine environmental protection. IMO, as the sole recognized body, is responsible for establishing ships' routing, which includes traffic separation schemes, traffic lanes, separation zones, recommended routes, deep-water routes, precautionary areas, and areas to be avoided. IMO also focused attention on peculiar aspects that condition routing and then navigation. For instance, weather routing was recommended by IMO's Resolution A.528(13) in 1983 (IMO, 1983) to assist ships in handling hazardous weather conditions. More recently, the environmental issues related to the preservation of seas and oceans have received growing attention. This has led for instance to the designation of the Emission Control Areas (ECAs), and the Particularly Sensitive Control Areas (PSSAs), in which navigation is regulated by specific measures.

The Annex VI "Regulations for the prevention of air pollution from ships" of the International Convention for the Prevention of Pollution from Ships (MARPOL) sets for each ECA a more stringent control on emissions of sulphur oxide (SOx) or of nitrogen oxides (NOx), which splits ECA into the two subgroups of SECA and NECA. PSSAs are designated by IMO in alignment with UN Sustainable Development Goal 14, aimed at protecting ecologically, socio-economically, or scientifically significant sea regions. These areas may have special protective measures, such as compulsory ship routing or designated areas to be avoided (IMO, 2005). PSSAs currently includes 18 areas worldwide, with the European Commission (EC) aiming to increase the PSSA share to 30% of European navigable waters by 2030.

In this work, we focus on the Mediterranean Sea, which is included among the four lighthouse areas of the EU Mission "Restore our ocean and waters by 2030" (European Commission, 2021) due to the environmental impact of the intense shipping occurring in its basin. The designation

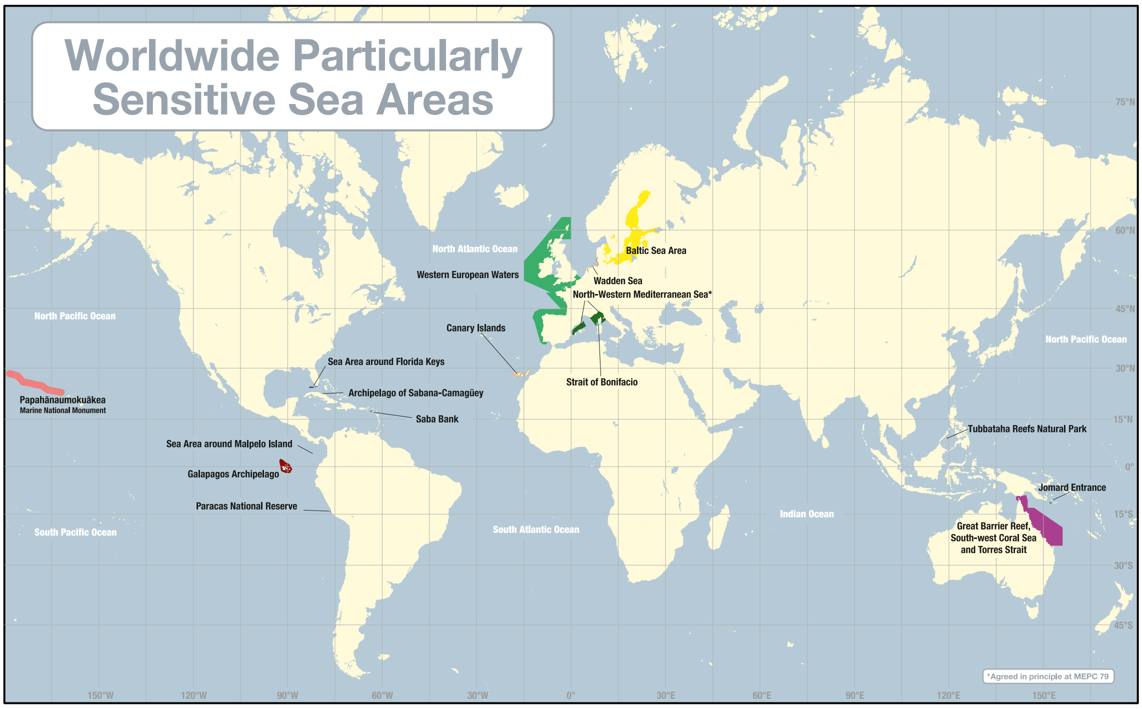

Figure 1 – *The official IMO map depicting the PSSAs over the world in 2023 (downloadable here). The European Commission prospects to increase the PSSA share to 30% of European navigable waters by 2030.*

of the Mediterranean Sea as a whole SECA under MARPOL Annex VI will enter into force next year. Besides, it already houses two PSSAs: the Strait of Bonifacio Area and the North-Western Mediterranean Area (Marine Environment Protection Committee (MEPC), 2023). We present a novel optimization problem for maritime transport under PSSA constraints, and we develop a Mixed-Integer Linear Programming mathematical model. Through simulation, we show that the developed approach enables ship owners to minimize costs while complying with PSSA regulations. Figure 1 shows a map of the current PSSAs on the planet.

A vast literature exists about a variety of different ship routing problems, and the related operation frameworks. Due to the lack of space, in this abstract the authors only mention the most recent and comprehensive papers among the pertinent ones. In (Bektaş *et al.*, 2019) the authors provide an overview of the application of Operational Research methods to greening maritime transportation, with reference to freight. Novel approaches to ship routing brought about by digitalisation are addressed in several works, such as (Yan *et al.*, 2021), a survey about the use of data analytics to manage vessels' fuel consumption. A valuable review of the literature about the optimization of ship voyage based on the control of noxious emissions is reported in (Yu *et al.*, 2021). On the other hand, the determination of vessel routes and speed in non-favorable weather conditions is addressed by Zis *et al.* (2020).

So far, a small portion of the literature on maritime routing has considered regulations aimed at preserving endangered or protected animal species inhabiting the seas and oceans, e.g., thresholds on noise pollution and ship speed limits, as a constraint on the maritime route planning. As highlighted by Jalkanen *et al.* (2022), who described the extent and environmental impact of underwater noise emissions from 2014 to 2020, noise pollution poses a threat to marine life and diversity. The application of ship speed limits also constitutes a current challenge in maritime optimization, due to the strict ship scheduling plans (Ng, 2022). Furthermore, few works in the literature consider stochastic data (Yu *et al.*, 2021). On the other hand, PSSA constraints are stochastic by nature. Indeed, as opposed to ECA regulations, that control emissions through rule applications, PSSA regulations prompt shipowners to react to unexpected events, e.g., sightings or migration of protected species, and reprogram ship routes.

In this work, we aim at closing these gaps. Specifically, we address the emerging need for strategies to efficiently navigate PSSAs (Choi, 2022). We present a novel optimization problem for maritime transport under PSSA constraints, and we develop a Mixed-Integer Linear Programming mathematical model. Through simulation, taking the Mediterranean Sea as a case study, we show that the developed approach enables ship owners to minimize costs while complying with PSSA regulations.

2 Problem statement, methodology and results

Given a fleet of vessels and a maritime network, the problem is to determine the routes of each vessel over the network so as to both satisfy the PSSA constraints over each sea leg and minimize the total transportation and penalty costs for the ship owner.

Formally, let $\mathcal{V}$ be a set of vessels. Each vessel $v \in \mathcal{V}$ is characterized by i) a fixed port rotation, ii) a time window for the arrival and departure times at each port, iii) an electric or fuel engine, or both, and iv) a type among ferry, tanker, and container ship. The type of a vessel affects its fuel and electricity consumption as well as its navigation capabilities through PSSAs. We model the maritime network as a multigraph $G = (\mathcal{P}, \mathcal{E})$, where $\mathcal{P}$ is a set of vertices, each representing a different port, and $\mathcal{E}$ is a set of arcs, each corresponding to a distinct sea leg. More specifically, $\mathcal{E}$ is encoded as a collection of set of arcs given by $\{\mathcal{E}_p^q, \forall p, q \in \mathcal{P}, p \neq q\}$, where $\mathcal{E}_p^q$ is the set of directed arcs from port p to port q. Each arc e is characterized by i) a length l_e of the sea leg associated with e, ii) constraints on noise pollution or harmful emissions, or both, which force the vessel to switch to an electric engine, iii) a set of allowed vessel types, and iv) a maximum allowed speed for each vessel that is traversing the sea leg. Observe that the constraints on the navigation through arc e account for the PSSA regulations aimed at safeguarding underwater fauna and ecosystem. We also consider unforeseeable marine life occurrences on each sea leg, such as the unexpected traversal of cetaceans. Given a number of time slots $K \geq 0$, we consider a time horizon partitioned into a set of time slots $\mathcal{T} = \{1, 2, \ldots, K\}$. At each $t \in \mathcal{T}$, the sightings or traversal of protected species through e may change its seaworthiness, by disallowing further vessel to enter e, and forcing vessels currently navigating through e to switch to an electric engine to reduce emissions and noise pollution. As a consequence, it is necessary to dynamically reprogram ship routes through areas with changed navigational conditions. The objective is to minimize the overall transportation costs of the fleet, while respecting all the constraints imposed by sea laws and satisfying the requirements on the time window of each ship.

We present a two-stage optimization algorithm that exploits a Mixed-integer Linear Programming (MILP) model of the problem. The "lower level" solves the MILP model through branch-and-bound at the beginning of the time horizon and for each occurrence of an unexpected event that requires a change in the planned maritime routes (in the latter case, the MILP model is solved over the remaining portion of the time horizon and only for those ships who have yet to reach their destination port). The "upper level" is responsible for detecting the events, determining whether a change in the planned maritime routes is required or not, and it also defines the instance of the problem when replanning is actually required. The "lower level" has been implemented with an algorithm developed in Python 3.10 with CPLEX API 22.1.0. The experimental results show that the algorithm is able to determine the maritime routes of a fleet consisting of up to 25 vessels on a network model that include 20 ports and 70 sea legs over a time horizon corresponding to 168 hours, i.e., 1 week time. Such a planning horizon allows a fine discretization, i.e., 15 minutes for each time slots, that yields a total of 672 time slots for the whole time horizon.

3 Discussion and conclusions

In this work, we propose a first model to determine ship routing through PSSAs under time-varying conditions. The solution algorithm is able to redetermine routes to comply with the changes in the constraints to PSSA navigation whenever an expected event occurs. It is compelling to pave the way to the development of more results on the navigation through PSSAs in light of the regulations and prospects of endangered species protection and decarbonization issued by IMO and the EC for the current and the next decade, also taking into account the different scenarios resulting from the progressive designation of new PSSAs in the years to come. Indeed, we prospect to expand the current model to gradually encompass all the real-world characteristics of maritime navigation. First, we will distinguish different types of vessels for both freight (containerships, tankers, bulk carriers, ...) and passengers (cruise ships, ro-ro ferries, ...). Different vessels may be subject to different rules when navigating (portions of) PSSAs. Besides, the physical characteristics of vessels may be taken into account to more accurately model their navigation through PSSAs. Another direction for development includes considering port operations and their effects on the satisfaction of time windows and coastal marine life. Such an extension would allow us to include not only the arcs but also the activities carried out in the nodes (ports) within the maritime transportation network. Regarding port operations, an interesting extension could be to consider charging/recharging plans for hybrid/electric vessels in the fleet, possibly adopting real-world schemes for electricity prices, such as Time-of-Use or Real-Time pricing (Catanzaro *et al.*, 2023).

As regards methodology, we will develop ad-hoc heuristics and metaheuristics to efficiently provide a tighter primal solution to the MILP model and, as a result, increase the computational efficiency of the algorithm. Finally, we will evaluate the efficacy of valid inequalities in strengthening the formulation and leading to faster performances.

References

Bektaş, Tolga, Ehmke, Jan Fabian, Psaraftis, Harilaos N., & Puchinger, Jakob. 2019. The role of operational research in green freight transportation. *European Journal of Operational Research*, **274**(3), 807–823.

Catanzaro, Daniele, Pesenti, Raffaele, & Ronco, Roberto. 2023. Job scheduling under Time-of-Use energy tariffs for sustainable manufacturing: a survey. *European Journal of Operational Research*, **308**(3), 1091–1109.

Choi, Junghwan. 2022. Assessing the need for the designation of the Yellow Sea Particularly Sensitive Sea Area (PSSA). *Marine Policy*, **137**, 104971.

European Commission. 2021. European Missions. Restore our Ocean and Waters by 2030 - Implementation Plan.

IMO. 1983. Resolution A.528(13) - Recommendation on weather routeing.

IMO. 2005. Resolution A.982(24) - Revised guidelines for the identification and designation of Particularly Sensitive Sea Areas.

Jalkanen, Jukka-Pekka, Johansson, Lasse, Andersson, Mathias H., Majamäki, Elisa, & Sigray, Peter. 2022. Underwater noise emissions from ships during 2014–2020. *Environmental Pollution*, **311**, 119766.

Marine Environment Protection Committee (MEPC). 2023. Resolution MEPC.380(80) - Designation of the North-Western Mediterranean Sea as a Particularly Sensitive Sea Area.

Ng, ManWo. 2022. On the Feasibility of Speed Limits in Ocean Container Shipping. *Maritime Transport Research*, **3**, 100067.

Yan, Ran, Wang, Shuaian, & Psaraftis, Harilaos N. 2021. Data analytics for fuel consumption management in maritime transportation: Status and perspectives. *Transportation Research Part E: Logistics and Transportation Review*, **155**, 102489.

Yu, Hongchu, Fang, Zhixiang, Fu, Xiuju, Liu, Jingxian, & Chen, Jinhai. 2021. Literature review on emission control-based ship voyage optimization. *Transportation Research Part D: Transport and Environment*, **93**, 102768.

Zis, Thalis P.V., Psaraftis, Harilaos N., & Ding, Li. 2020. Ship weather routing: A taxonomy and survey. *Ocean Engineering*, **213**, 107697.