DEPARTMENT OF INTERNATIONAL AND EUROPEAN ECONOMIC STUDIES

ATHENS UNIVERSITY OF ECONOMICS AND BUSINESS

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Olympia Nisiforou

Chris Deranian

Angelos Alamanos

Jorge Andres Garcia

Phoebe Koundouri

Working Paper Series

25-07

January 2025

MODELING ADAPTIVE STRATEGIES TECHNOLOGIES TOWARDS CLIMATE-NEUTRAL SHIPPING

Olympia Nisiforou, Cyprus University of Technology, Olympia.nisiforou@cut.ac.cy
Chris Deranian, Athens University of Economics and Business, chris.deranian@gmail.com
Angelos Alamanos, Independent Researcher, Germany
Jorge Andres Garcia, The Water Institue, Univeresity of Waterloo, ja4garci@uwaterloo.ca
Phoebe Koundouri, Athens University of Economics and Business; ATHENA Research Center; Denmark Technical University, pkoundouri@aueb.gr

Overview

The maritime sector faces multiple techno-economic, environmental and development challenges, requiring careful investment decisions. The need for holistic solutions that can address these considerations simultaneously is becoming increasingly pressing. In this paper we present the application of a free, open-source Investment Decision Support Tool, called MaritimeGCH: a least-cost linear optimization model that reflects operational and investment variables and constraints within the shipping industry. The model aims to optimize fleet composition under techno-economic, environmental, operational factors and European environmental regulations. Through this, we are able to test the effect of different technologies, their respective costs and carbon abatement potential within the Greek shipping fleet. China has the largest maritime fleet globally, with a merchant fleet of 249.2 million gross tonnes, overtaking Greece, while Greece follows closely with about 249 million GT. Greece ranks first in deadweight tonnage (DWT), accounting for 17.77% of the global capacity, with a fleet of 364 million DWT. This importance stems from a deep-rooted tradition of maritime expertise and a strategic focus on global shipping markets, positioning it as a crucial component of international trade and economic stability (Alexandropoulou et al., 2021; Papandreou et al., 2021)

Methods

The MaritimeGCH model is an advanced optimization Investment Decision Support Tool (IDST) (Alamanos et al., 2024). It is based on optimization, namely it describes mathematically the problem that needs to be tackled , in the best possible way, satisfying many (often conflicting) objectives. The model uses linear programming (LP) to minimize the total cost of fleet operations over a user-defined planning horizon (in this case 2020-2050). It includes decision variables (e.g., fleet composition, fuel choices), objective function (e.g., minimizing total cost), and constraints (e.g. emissions caps, shipping demand, technological limitations, etc.). The objective function of the model is to minimize the total cost over the planning horizon (2020-2050), as shown in Equation 1 below:

$$min \sum_{y=2020}^{2050} \left(total\_cost_y\right) \quad \text{Total cost in year y (in million Euros)} \quad (1)$$

Such that total cost is:

$$total\_cost_y = \sum_s \left(new\_ship_{y,s} \times invest\_cost_s\right) + \sum_s \left(stock\_ship_{y,s} \times op\_cost_s\right) + \sum_s \left(fuel\_demand_{y,f} \times fuel\_cost_f\right) + \left(excess\_emissions_y \times ETS\_price_y\right) \quad (2)$$

Through this tool we are able to test the effect of different adaptive technologies to make shipping greener, subject to our constrains. Embedding cost and carbon abatement within operational parameters of the model allow both new and existing ships to adopt these technologies. Potential technologies include engine power optimization, using advanced fuel injection systems, route optimizer technology, port-call technology for optimal entrance to a port, propulsion-assist systems (e.g. wind-assisted propulaion, air lubrication systems, or alternative fuel propulsion systems), hull cleaning and maintenance measures. A combination of these measures is also tested to run mixed measure scenarios.

Results

We see the results of a combination scenario of adaptive strategies indicatively in Figure 1 below. The results show an illustrative fleet evolution, investment, and operational metrics until 2050. As assumed, there is a steady growth in the shipping demand services which requires a respective increase in the number of vessels for its coverage (exceeding 1,400 vessels by 2050). The investment costs remain relatively stable from 2020 to 2045, while a growing fleet rises consistently the operational costs, reflecting also the adoption of the various technologies. The fuel demand distribution shows a declining reliance on oil as cleaner fuels gain prominence, indicating a strategic shift towards sustainability. Moreover, it shows that the CO2 emission are gradually reducing. This is an important finding, proving that although the shipping demand and the fleet size increase, the transition to cleaner fuels and the adoption of emission reduction technologies can outweigh that. The propulsion one has the biggest effect on fuel consumption reduction, and subsequently, on emissions reduction – but all technologies are needed as a combination for best results. In addition, focusing on propulsion it can be seen that it has the most significant impact on decreasing fuel consumption, and consequently on reducing emissions,. Nevertheless, a combination of all technologies is required for optimal outcomes. According to Maritime EU Emissions Trading System (EU ETS) regulatory framework assumption, an increasingly stringent cap is observed, though instances of excess emissions are evident in the early periods. These excess emissions drive the “EU ETS Penalty” costs, imposed when fail to comply with its requirements which spike notably during periods of non-compliance.

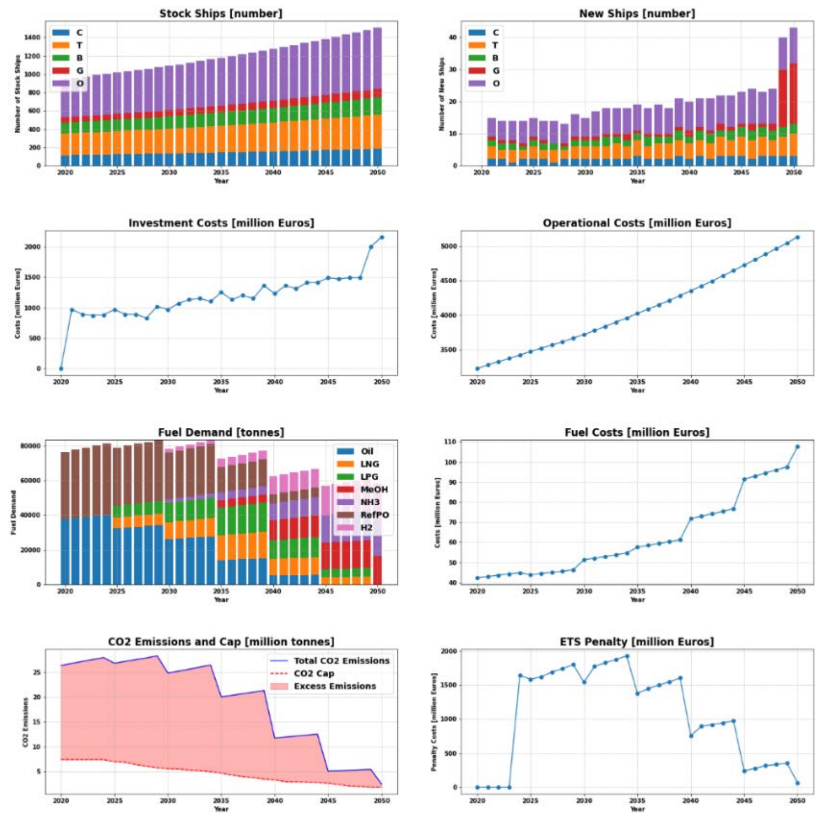

Figure 1. Results of the application to the Greek fleet, including: the fleet composition (stock and new ships); investment and operational costs; fuel demand and the associated costs; the CO2 emissions compared to the ETS threshold, and the associated penalty.

Conclusions

The development of this open-source optimization tool represents a critical breakthrough in addressing the maritime sector's decarbonization challenge. The suggested integrated modeling approach not only provides a practical mechanism for fleet operators to reduce carbon emissions but also serves as a scalable framework for systemic change. The tool's ability to dynamically balance economic feasibility with environmental imperatives highlights a key insight: decarbonization is not a binary choice between profitability and sustainability, but a nuanced optimization problem that requires sophisticated analytical capabilities. In this vein, the tool provides the opportunity to evaluate different costs and benefits of technological adaptation needed to reduce emissions in shipping. If these actions are not enough to reach net zero targets, more collective action will be needed from the shipping industry to reach net zero.

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