MODELING ADAPTIVE STRATEGIES TECHNOLOGIES TOWARDS CLIMATE-NEUTRAL SHIPPING

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Overview

The maritime sector faces multiple techno-economic, environmental and development challenges, requiring careful investment decisions. 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. Greece has the second largest fleet globally, with a merchant fleet of about 249 million gross tonnes. 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:

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

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:

- Optimizing engine power: tuning engines for efficiency, potentially using advanced fuel injection systems, and optimizing speed for reduced fuel consumption and emissions [engin_opt]
- Route Optimizer technology to reduce emissions: real-time weather and sea conditions to determine the most fuel-efficient and emissions-saving routes [route_opt]
- Port-call technology for optimal entrance to a port: streamline vessel arrival times to ports, reducing idle time, fuel consumption, and emissions during waiting periods [port_call]
- Propulsion system: more efficient systems, such as wind-assisted propulsion, air lubrication systems, or alternative fuel propulsion systems [propul]
- Hull cleaning and maintenance: technologies to clean the ship aiming at reduced traction, and subsequently emissions [hull]

A combination of these measures is also tested to run mixed measure scenarios.

Results

We see the results of a technology combination scenario of adaptive strategies indicatively in Figure 1 below. 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). 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, reducing emissions. This is an important finding, proving that although shipping demand increases, the transition to cleaner fuels and the adoption of emission reduction technologies can outweigh that. The propulsion system has one the biggest effects on fuel consumption and emissions reduction, but all technologies are needed as a combination for best results. According to Maritime EU Emissions Trading System (EU ETS) regulatory framework assumption, an increasingly stringent cap is observed, where 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; investment and operational costs; fuel demand; 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 flexibility 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 the 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.

References

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