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SUSTAINABLE FLEET OPERATIONS THROUGH INTEGRATED OPTIMIZATION UNDER TECHNO-ECONOMIC SHIPPING AND ENVIRONMENTAL CONSTRAINTS

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Sustainable fleet operations through integrated optimization under techno-economic shipping and environmental constraints

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Abstract

The maritime sector faces increasing challenges as part of its ongoing transformation period towards more sustainable shipping: There is a shift in fuel preferences, with a gradual phasing out of high-polluting options in favor of cleaner, more sustainable alternatives, amidst increasingly stringent environmental policies pushing for greenhouse gases (GHG) emissions reduction, on top of the already complex techno-economic considerations for optimal shipping operations. These multifaceted challenges call for sophisticated, holistic solutions that can address economic, environmental, and operational aspects simultaneously. In response, the Global Climate Hub (GCH – an initiative under the UN Sustainable Development Solutions Network) develops integrated models to assess such problems and provide sustainable pathways. Here, we present such a model, the MaritimeGCH, a free, open-source, simple and comprehensive tool to address such challenges of maritime fleet management. MaritimeGCH integrates different techno-economic, environmental, operational factors and recent European environmental policies into a single, comprehensive model, which is at the same time simple and transferable to various scales. The optimization logic is first described for maritime problems; next the detailed mathematical description of MaritimeGCH model is presented; and finally, its potential for policy-relevant scenario analysis is outlined with specific examples. The model is publicly available to encourage similar applications and improvements.

Keywords: MaritimeGCH; Global Climate Hub; Fleet Optimization; Shipping; Sustainable maritime operations; Environmental regulations; Techno-economic analysis.

1. Modern Sustainable Shipping

The maritime industry faces unprecedented challenges in the recent decades, including stricter environmental regulations with the urgent need to reduce greenhouse gases (GHG) emissions, volatile economic conditions and fuel prices, as well as changing trends in fuel types, with the more polluting ones fading and being replaced by greener ones. All these reflect the need for the maritime sector's sustainability transition, aiming to reduced emissions and pollution, at the same time where increasing needs and demand for shipping services must be also met. As global trade continues to grow, shipping companies must balance economic viability with environmental sustainability, all while navigating complex operational constraints and evolving international policies.

Such policies become increasingly evident in the maritime sector, and (e.g. for European shipping) include the Carbon Intensity Indicator (CII), the Annual Efficiency Ratio (AER), and the European Emissions Trading System (ETS). These regulations encourage ship operators to improve their energy and operational efficiency, and reduce their carbon footprint, by using different compliance metrics.

The CII was introduced by the International Maritime Organization (IMO) as part of its strategy to reduce GHG emissions from ships (IMO, 2021). It was adopted in 2021 and became effective from January 2023. The CII aims to measure and control the carbon intensity of ships, which is the amount of CO_2 emitted per unit of transport work (Faber et al., 2020). The CII is calculated annually for each ship and based its value, the ships are rated on a grading scale from A to E based on their performance. Ships with poor ratings (D or E) must submit corrective action plans to improve their CII.

The AER is another metric (equivalent to CII) developed by the IMO to assess the energy efficiency of ships. It has been in use since the early 2010s as part of the Energy Efficiency Design Index (EEDI) framework (IMO, 2016; Johnson et al., 2013). The AER measures the CO_2 emissions per transport work (e.g., per tonne-mile) over a year, so it is estimated as the ratio of the annual CO_2 emissions to the annual transport work. AER is then used to benchmark ships against efficiency standards and identify areas for improvement (e.g., to optimize routes, speeds, and operational practices to reduce emissions).

The ETS was launched in 2005 as the world's first major carbon market. It initially covered sectors like power and manufacturing but has been expanded to include maritime transport since January 2024. The ETS aims to reduce GHG emissions by setting a cap on the total amount of certain GHGs that can be emitted by installations covered by the system (European Commission, 2021; Psaraftis, 2019). Companies must hold sufficient allowances to cover their emissions, incentivizing them to reduce emissions, or – if they exceed them, to buy additional allowances. So, maritime transport operators must monitor and report their CO_2 emissions, in order to receive (or purchase) emission allowances, which they can trade with other operators. If emissions exceed the allowances, operators must buy additional allowances or face penalties.

The new considerations arising from this regulatory space, together with the economic and demand challenges mentioned above for the shipping sector constitute a complex and dynamic problem for achieving sustainable shipping. The Global Climate Hub (GCH) initiative is committed in providing scientific solutions in such problems. Under the UN’s Sustainable Development Solutions Network (SDSN, 2022), we developed the GCH (SDSN, 2024), an international research-led initiative, hosted by Athens University of Economics and Business (AUEB) and the “Athena” Research and Innovation Center. The GCH's approach is based on the combination of cutting-edge models describing cross-sectoral system-dynamics for all major natural and infrastructure systems, including the maritime sector, and socio-economic narratives to bring the scientific insights in the society (Alamanos, 2024; Koundouri et al., 2024). The whole process of analyzing, co-designing with key stakeholders, presenting and applying sustainable pathways supports the widespread adoption of the principles of Open Science and Open Access to data, models developed, and in general scientific infrastructure.

In this chapter, we present how such complex maritime problems can be approached by the GCH. In particular, how to analyze them as optimization problems, describe them mathematically, and we design such models in detail: We present the MaritimeGCH model, designed by the GCH, in order to assist addressing such complex challenges.

2. Optimization for maritime operations

Complex maritime problems involving economic, environmental, technical shipping factors, operational concerns, and restrictive regulations can be effectively expressed as optimization processes. Optimization is a mathematical representation of a problem that we want to solve with the best possible way, satisfying many (often conflicting) objectives. The solutions of such problems are not evident or clearly standing out, so optimization formulates the problems in a structured way and help us solve them while quantifying the impacts of these solutions (Alamanos and Garcia, 2024). These processes aim to achieve a specific objective, such as minimizing total costs or maximizing efficiency, while adhering to a set of constraints that represent real-world limitations and regulatory requirements (Garcia and Alamanos, 2023). In the maritime industry, this approach allows decision-makers to balance competing factors like fuel costs, emissions regulations, fleet capacity, and operational efficiency (Wang et al., 2021).

The most common optimization process is linear programming (LP) due to its ability to reach solutions without being too complex and computationally heavy. LP assumes a linear objective function (Z) which is set as a goal for maximization or minimization, under linear constraints, all functions of the decision variables (Equation 1):

$$\text{max (or min) } Z = f(x_1, x_2, \dots, x_n) \qquad (1)$$

where $x_1, x_2, \dots, x_n$ are the decision variables, that will define the optimal solution. In addition, ‘Z’ must satisfy a set of constraints, the acceptable range of values (Equation 2):

$$u_i(x_1, x_2, \ldots, x_n) \leq a_i, \quad \forall i \tag{2}$$

where a_i: known values (the problem's data). The optimum solution of the system must meet all the constraints and the objective function.

This practically provides a useful set-up for several problems, because an objective (goal) can be maximized or minimized, while exploiting the optimum levels of the other parameters of the system (controlled as constraints), all depending on the decision variables (Zhou et al., 2021).

Maritime optimization models typically include decision variables (e.g., fleet composition, fuel choices), an objective function (e.g., minimizing total cost), and constraints (e.g., similar to the aforementioned regulations or emissions caps, shipping demand, technological limitations, etc.) (Han et al., 2023). The results of these approaches enable shipping companies and policymakers to make informed decisions that consider the complex interplay between economic viability, environmental sustainability, and regulatory compliance.

Maritime fleet optimization has been explored through the lens of optimization modelling, primarily focusing on economic objectives such as cost minimization (Al-Enazi et al., 2022). there have been studies optimizing fleet composition, routing, and scheduling to reduce operational costs (Psaraftis et al., 2013; Meng et al., 2014). However, with increasing environmental concerns, there has been a growing interest in incorporating emissions reduction into maritime optimization models (Perčić et al., 2021). Some recent works have explored the integration of emissions constraints and the use of alternative fuels to minimize the environmental impact of shipping operations (Faber et al., 2020; Johnson et al., 2013). The SEAMAPS model is another example of an integrated advanced least-cost fleet optimization approach, considering techno-economic parameters and environmental concerns through different fuel types and general emissions taxes (Franz et al., 2022; Franz and Bramstoft, 2024). Despite these advancements, to our knowledge, there is no comprehensive approach that simultaneously addresses economic, environmental, and technical factors while also incorporating recent European policies such as the CII and AER, and the ETS, while also considering greener shipping through alternative fuel types. In the next section we present how the MaritimeGCH model contributes towards this direction by providing a holistic and simple optimization framework.

3. The MaritimeGCH model: Mathematical Description

The MaritimeGCH model is an advanced optimization tool designed to tackle these multifaceted maritime challenges. The model is comprehensive and simple, in order to allow stakeholder engagement and potential analysis of different scenarios (Alamanos et al., 2024). It uses LP to minimize the total cost of fleet operations over a user-defined planning horizon. It takes into account the CII (and AER) and ETS regulations that might take effect (or change) during the planning period. It also takes into account a wide range of parameters, including ship and engine types, age and lifetime of ships, fuel types and their availability over the planning horizon, fleet capacities, shipping demand, ship production capacity, investment and operational costs, fuel costs, CO_2 emissions (Table 1).

Table 1. The detailed mathematical description of the model with explanatory comments.

<u>**Sets and Indices**</u>

- **years:** Set of years, expressing the planning horizon, indexed by y. In this example, we assume this period to be from 2020 to 2050.
- **ship_types**: Set of ship types, indexed by s. These can be for instance: Container, Tanker, Bulk, Cargo, Other.
- **fuel_types**: Set of fuel types, indexed by f. These can include for example: Marine Fuel Oil or Heavy Fuel Oil (Oil), Liquefied Natural Gas (LNG), Liquefied Petroleum Gas (LPG), Methane (MET), Methanol (MeOH), Ammonia (NH_3), other alternative fuels except of LNG (AllNoLNG), refined petroleum oils (RefPO), Hydrogen (H_2), or other fuel blends allowing different mixes, which is often the case when ships refuel at different ports.
- **engine_types**: Set of engine types, indexed by eng, incuding: ME-C engine, ME-GI (high pressure gas engine), ME-LGI (liquid gas injection), or Multi-Fuel Engines (MFE).

<u>**Parameters** (the model's data or assumptions)</u>

- **invest_cost$_s$**: Investment cost of ship type s (in million Euros).
- **op_cost$_s$**: Operational cost of ship type s per year (in million Euros).
- **fuel_cost$_f$**: Fuel cost of fuel type f (in Euros per tonne).
- **emissions_factor$_f$**: Emission factor of fuel type f (tonnes of CO_2 per tonne of fuel).
- **co2_cap$_y$**: CO_2 emissions cap (threshold) in year y (tonnes of emitted CO_2). If the company exceeds that, then they will have to buy CO_2 emissions allowance (see next bullet), according to the ETS.
- **ETS_price$_y$**: Cost per tonne of CO_2 for emissions exceeding the cap in year y (Euros per tonne of CO_2).
- **prod_capacity$_{y,s}$**: Production capacity of ship type s in year y (number of ships that can be produced).
- **lifetime$_s$**: Lifetime of ship type s (in years).
- **fuel_consumption$_{s,f,eng}$**: Fuel consumption of ship type s using fuel type f (tonnes of fuel per year) per engine type eng.
- **demand_shipping$_{y,s}$**: Demand for shipping services in year y [Gross Tonnage per Nautical Mile (GtNM)] of ship type s in year y.
- **init_capacity_fleet**: Initial capacity of fleet of ship type s in the year 2020 (number of ships).
- **fleet_age**: the initial (average) age of the fleet, per ship type (years).
- **fuel_avail$_{f,y}$**: Available amount of fuel type f that can be used per year y (tonnes).
- **cap$_s$**: Capacity, namely the weight of each ship types' load (GtNM).
- **CII$_{desired,s}$**: Desired value of Carbon Intensity Indicator of ship type s (or equivalently the AER class).

Decision Variables

- **new_ship_y**: Number of new ships of type s in year y.
- **$stock\_ship_y$**: Stock of ships of type s in year y.
- **$fuel\_demand_{f,y}$**: Fuel demand of fuel type f in year y (tonnes).
- **$co2\_emissions_y$**: CO_2 emissions in year y (tonnes of CO_2).
- **$excess\_emissions_y$**: Excess CO_2 emissions above the cap in year y (tonnes of CO_2).

Objective Function = Minimize the total cost over the planning horizon (e.g., 2020-2050):

$$min \sum_{y=2020}^{2050}(total\_cost_y) \quad \text{Total cost in year y (in million Euros)} \quad (3)$$

Where:

$$total\_cost_y = \sum_s(\text{new\_ship}_{y,s} \times \text{invest\_cost}_s) + \sum_s(\text{stock\_ship}_{y,s} \times \text{op\_cost}_s) + \sum_s(\text{fuel\_demand}_{y,f} \times \text{fuel\_cost}_f) + (\text{excess\_emissions}_y \times \text{ETS\_price}_y) \quad (4)$$

Constraints:

Fleet Capacity Constraint: The total stock of ships each year must be sufficient to meet the demand for shipping services:

$$\sum_s(\text{stock\_ship}_{y,s} \times \text{cap}_s) \geq \text{demand\_shipping}_y \quad \forall \text{y} \quad (5)$$

Ship Production Constraint: The number of new ships built each year is limited by production capacity:

$$\text{new\_ship}_{y,s} \leq \text{prod\_capacity}_{y,s} \quad \forall \text{y, s} \quad (6)$$

Fleet Stock Update Constraint: The stock of ships of each type in a given year is the sum of new ships built and surviving ships from previous years, based on their lifetime and age:

If y=2020, $\text{stock\_ship}_{y,s} = \text{init\_capacity\_fleet}_s$ (7)

Else: $\text{stock}_{\text{ship}_{y,s}} = \text{new}_{\text{ship}_{y,s}} + \text{stock}_{\text{ship}_{y-1,s}} - \text{retired}_{\text{ships}_{y,s}} \quad \forall \text{ y, s} > 2020$ (8)

Where: $\text{retired}_{\text{ships}_{y,s}} = \sum_{y,} \text{new\_ship}_{y\prime,s}$ (9)

for y’ ∈ [max (2020, y - lifetime[s] + 1 - fleet_age[s]), y-1] (10)

Fuel Demand and Availability Constraints: The fuel demand is derived from the operational needs of the ships, which however, cannot exceed the available amount of each fuel type this year:

$$\text{fuel\_demand}_{y,f} = \sum_{s,eng} \text{stock\_ship}_{y,s} \times \text{fuel\_consumption}_{s,f,eng} \quad \forall \text{ y, f, s}, eng \quad (11)$$

And $\text{fuel\_demand}_{y,f} \leq fuel\_avail_{f,y} \; \forall \text{ y, f}$ (12)

Emissions Constraint: The total CO_2 emissions are calculated based on fuel consumption:

$$\text{co2\_emissions}_y = \sum_f \text{fuel\_demand}_{y,f} \times \text{emissions\_factor}_f \quad \forall y \qquad (13)$$

ETS Emissions Cap Constraint: The total CO_2 emissions in each year must not exceed the cap threshold plus any excess emissions (which will have to be then purchased):

$$\text{co2\_emissions}_y \leq \text{co2\_cap}_y + \text{excess\_emissions}_y \quad \forall y \qquad (14)$$

And $\text{excess\_emissions}_y \geq 0 \quad \forall y \qquad (15)$

With this approach we set a CO_2 emissions cap (threshold). B) We allow emissions to exceed this cap, but any excess is tracked, and 'penalized' with an additional cost in the objective function. This is a 'combined' approach (threshold-constraint and penalty), and it is realistic and effective, as it mirrors simply the actual ETS regulatory environment where companies can exceed their caps by purchasing allowances (European Commission, 2023; 2022).

Carbon Intensity Indicator Constraint: It should not exceed a performance defined by regulations, or the user/ owner ($\text{CII}_{desired\ per\ ship\ type\ s}$) in order to ensure that the ship will remain in the 'active' fleet:

$$\text{CII}_{s,y} \leq \text{CII}_{desired,s} \qquad (16)$$

The $\text{CII}_{desired,s}$ is actually the same/ equivalent approach as the AER, as they are based on almost the same equation and concept, to set an environmental standard to allow ships to travel. For example, in this constraint it can be reflected by setting the $\text{CII}_{desired,s}$ equal to the respective grade "C" (AER class) or better (B or A grade), because the regulation implies the ships not to travel if they are graded D (for three consecutive years) or below (IMO, 2022).

Where: $\text{CII}_{s,y}$ = Carbon Intensity Indicator of ship type s per year is estimated as (IMO, 2022):

$$\text{CII}_{s,y} = \frac{\text{co2\_emissions}_y}{\text{cap}_s} \qquad (17)$$

MaritimeGCH optimizes new ship acquisitions, existing fleet management, fuel consumption, and CO_2 emissions while adhering to operational and environmental constraints, in line with the existing policies.

4. The MaritimeGCH model: Data, code, results

The MaritimeGCH model, as outlined in the previous section, requires data on the carrying capacity of ships, the $\text{CII}_{desired,s}$, the CO_2 emissions cap, the demand for shipping services, the emissions factor, the ETS price, the fuel costs, consumption and availability, the initial fleet's ships, their age and lifetime, the production capacity, the investment and operational costs. All this data can be defined according to existing databases or according to the user's assumptions. The model requires each one of these datasets to be in a .csv format which gets read by the script. This approach makes it easy and scalable to any case-study scale (from local to global). Also, it allows the data to be flexible in terms of their units.

The MaritimeGCH model has been developed in Python programming language, an open-source code, freely available. The script is publicly available, in line with the open-source / open-science guidelines. The available script assumes an example with indicative data, just for the sake of demonstrating how the model operates.

The results provide the user with dynamic (annual) detailed cost breakdowns, CO_2 emissions, fuel demand, fleet composition per ship types, along with the new and stock ships per year, and the annual excess emissions over the ETS CO_2 cap. The model is designed to provide the detailed problem expression with all the parameters used – this is exported in a text file. All the model's outputs are provided in detailed tables, also automatically exported in an MS Excel file. Finally, the main results are exported automatically in a set of informative plots (Figure 1). The results' text, Excel and plots are directly saved in the user's working folder.

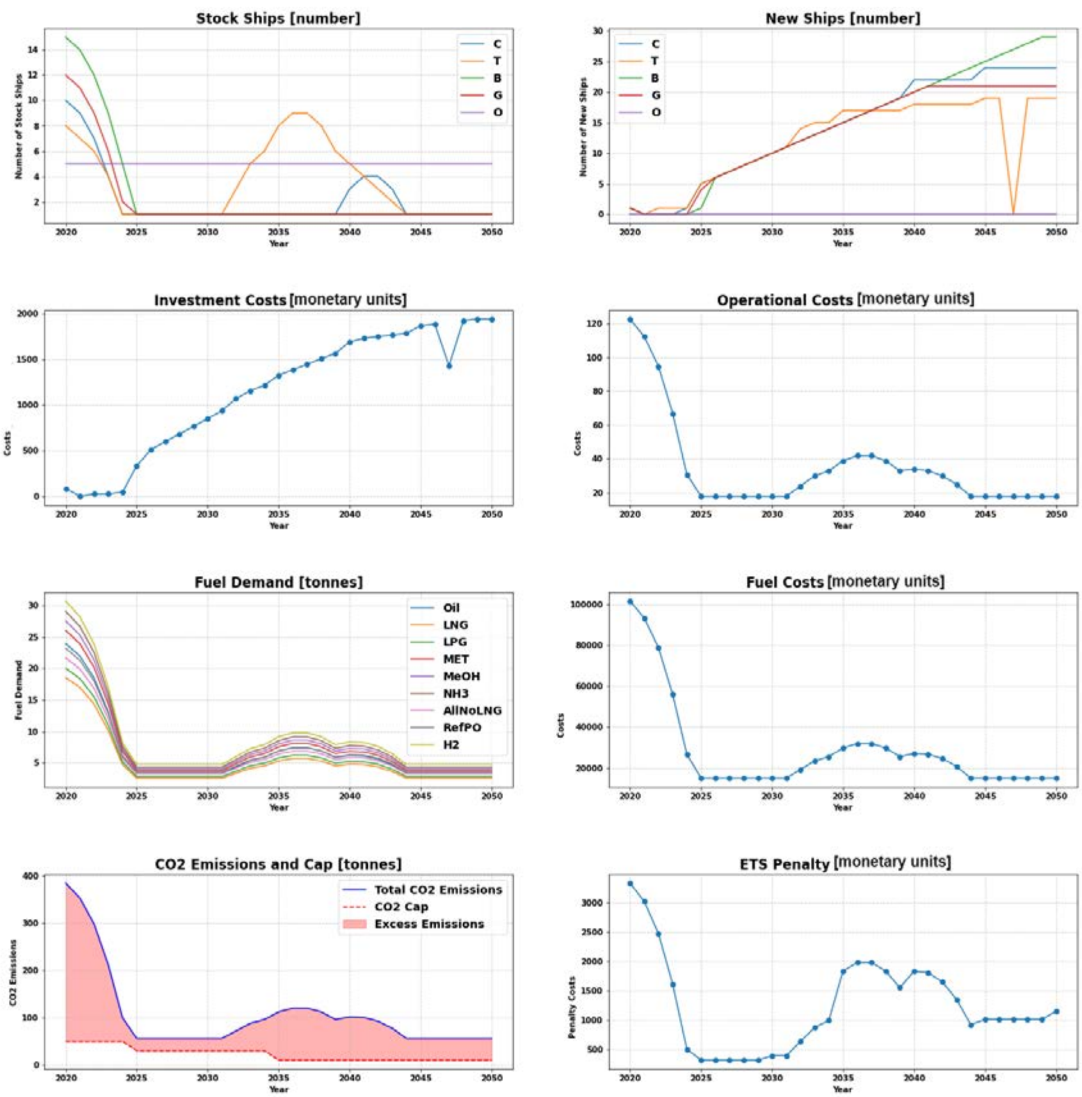

Figure 1. Indicative results of the model, with example data, for the sake of demonstration.

5. Potential for scenario analysis

Scenario analysis is a useful tool in optimization models, as they can provide analysts and policymakers with useful insights about different plausible situations. By evaluating different scenarios, such as variations in fuel costs, emissions regulations, and technological advancements, decision-makers can understand the range of possible outcomes and the robustness of their strategies (Koundouri et al., 2024). This approach helps in identifying optimal solutions that remain effective under varying conditions, thereby reducing risks and uncertainties (Keseru et al., 2021; Calado et al., 2021). For instance, in maritime fleet optimization problems similar to our model, scenario analysis can reveal how changes in fuel prices or emissions caps might impact total costs, fleet composition, and operational efficiency. This comprehensive understanding enables more informed and resilient decision-making, and such approaches are getting increasing attention in research (Ksciuk et al., 2023). Psaraftis and Kontovas (2013) developed a model to optimize ship speed and fleet size under different fuel price scenarios. Fagerholt et al. (2015) explored scenarios related to Emission Control Areas (ECAs). Their study showed how different regulatory scenarios could influence route planning and fuel choices for maritime fleets. Halff et al. (2019) examined scenarios involving the adoption of alternative fuels and propulsion technologies, highlighting how different technology adoption rates could affect fleet composition and emissions profiles over time. Wang et al. (2023) integrated both economic and environmental factors in their fleet optimization model, considering scenarios with varying fuel prices, emission regulations, and carbon pricing schemes, demonstrating the complex interplay between these factors in optimal fleet management.

The MaritimeGCH model allows the user to test different scenarios through running it under different input data, reflecting different conditions. The user can create for example, copies of the csv input data files and then test various values to the model's outputs. In this section we list the potential scenarios that can be explored in the model, and explain their policy relevance.

<u>Fuel costs</u>

The user can test different cases of fuel costs over the planning period by trying for instance low, average, and high costs. These can be inserted in the $fuel\_cost_f$ parameter. This is a crucial scenario analysis, as the economics of the fuels can vary significantly, and predicting them in the long-term is challenging (Yan et al., 2021). Providing insights of economic uncertainty is an important factor in the modeling process.

<u>CO_2 Emissions</u>

The user can also explore different scenarios of CO_2 emissions. By trying different input data of the $emissions\_factor_f$ dataset, the model can represent different conditions of emissions. This scenario exploration is very important for policymaking, as it can reflect different emission reduction technologies. They can be represented implicitly in the model as they have a certain cost (which can be added in the investment cost term or as a new term in the total cost function – see Equation 4), and can lead to a certain percentage of CO_2 emissions reductions. Some examples can refer to:

- Scrubbers technologies - systems installed on ships to remove harmful pollutants from exhaust gases before they are released into the atmosphere (Zis et al., 2021; Lunde Hermansson et al., 2024);
- Route Optimizer technologies (using advanced algorithms and real-time data to determine the most efficient path for a ship to travel) to reduce emissions by increasing fuel efficiency and reducing the distance covered (Wang and Meng, 2012);
- Port call technology for optimal timing and approach of ships entering a port. It uses real-time data on port conditions, traffic, and berth availability to determine the most efficient arrival time and speed for each vessel. So it has the potential to significantly reduce emissions associated with waiting times and speed (Nikghadam et al., 2024).
- Modern propulsion systems that have the potential to make such mechanisms more efficient, and hence, less emission-intensive (Inal et al., 2022; Nguyen et al., 2021).
- Technologies to keep the ship's hull clean and reduce its traction and resistance in water, which can subsequently reduce the associated emissions (Kim et al., 2024; Stark et al., 2022).

CO_2 emissions cap (threshold)

The CO_2 emissions cap, which is usually imposed by the respective policies, can also be a factor that the user might wish to explore. By trying different emissions thresholds or altering over the planning period, through changing the values of the $co2\_cap_y$ parameter, the analyst can see the impact of different policies. These can be observed in the costs, in the allowance that will need to be purchased according to the ETS, or the fleet composition to adhere to the different regulations. Three potential sets of scenarios that can be explored are:

- Running the model with and without the CO_2 emissions cap. The difference in the results will be the actual effect of the ETS regulation, offering "policy evaluation” insights.

- Running the model with different cap approaches, i.e., testing a lenient (loose), medium, and strict scenario of regulations, in terms of emissions allowance.
- Running the model with different variation of the CO_2 emissions cap, for example making it stricter earlier, or later during the planning horizon.

ETS price

The parameter ETS_price_y expressing the cost of the emissions exceeding the cap, can be another factor to explore different scenarios. Similar to the previous scenario approach on the emissions cap, the price for these excess emissions can reflect different degrees of policy “strictness”.

Transition to ‘greener’ fuels

The MaritimeGCH model assumes different fuel types and their availability over the years of the planning period. This is expressed by the $fuel\_avail_{f,y}$ input dataset. By making different fuel types less available over the years, while allowing other fuel types to become more or steadily available over time, the user can explore the effect of different decarbonization scenarios (transition to ‘greener’ fuels). For example, this can be explored by assuming some ‘polluting’ fuel types, like oil, fading over time, and others becoming more prevalent in the future (e.g., greener ones like H_2). So, by changing the respective data one can test three main decarbonization pathways:

- Fast;
- Medium;
- Slow;

and assess their impact on the overall model’s outputs and fleet decisions.

6. The way forward

In this chapter, the MaritimeGCH model, an integrated maritime fleet optimization model, was presented. Its mathematical description was outlined, and its potential for scenario exploration considering various policy-relevant cases was discussed.

Of course, no model is perfect, can give answers to any question, or comes without limitations. The MaritimeGCH model uses LP / dynamic programming (time-dependent problem), in order to keep the model simple and fast in reaching solutions, but other approaches can be used as well. Our future research plans include the use of fuzzy optimization, in which several parameters that might be uncertain, will be recognized as ranges of values throughout the model to provide ranges of results. Moreover, this chapter focused on the presentation of the conceptual model as a demonstration example, but our ongoing research focuses on the simulation of real-world case studies and fleets.

Currently, the model provides a number of practical and policy implications, which are important to summarize. First, it is worth mentioning that the planning horizon (in this example it was set from 2020 to 2050) is flexible, and the user can adjust it as desired. This is important for long-term fleet planning and strategic decision-making. This can help shipping companies and policymakers plan for gradual fleet renewal or technology adoption, and changes in the other parameters considered.

Another crucial aspect of the model is its ability to incorporate European regulations (such as the CO_2 emission caps, the ETS pricing mechanism and the CII compliance) with a simple and realistic way. This allows stakeholders to assess the impact of current and future environmental regulations on fleet operations and costs. The MaritimeGCH model contributes also to the sustainability transition insights for policymakers through its decarbonization analysis, which is achieved by the fuel types and their availability over time. This allows the user to explore real and hypothetical policy scenarios considering fuel transition strategies. By including various fuel types and their associated costs and emissions factors, the model can inform strategies for decarbonization through transitioning to cleaner fuels, which is (and will become) a core shipping concern. The model structure allowing for scenario analysis, enables stakeholders to explore different future scenarios, either management or hypothetical cases where different situations can be tested (e.g., varying fuel prices, demand patterns, or regulatory environments such as stricter emissions caps, changes in ETS pricing) along with their impacts on optimal fleet strategies and decarbonization efforts in the sector. This is a crucial process, especially in the maritime sector, as it has the potential to accelerate its decarbonization (Nisiforou et al., 2022).

Last but not least, the model is still able to provide answers to the more ‘traditional’ fleet operation considerations, including investment decision support, operational cost optimization, capacity planning, and technology adoption insights. In particular, since the model considers investment costs for new ships, it helps informing decisions about fleet renewal and expansion, specifically guiding shipowners on when and what types of ships to invest in. Furthermore, by factoring in operational costs and fuel consumption, the model can help optimize year-to-year fleet operations to minimize costs while meeting demand and environmental constraints. MaritimeGCH also takes into account constraints describing the shipping demand, fleet age, lifetime, capacity, and production limits, which enables the model to inform decisions about overall fleet capacity needs and how to meet changing demand patterns over time. Finally, through the scenario analysis, as discussed in the previous section, and the input data considering different efficiencies, emission factors or engine types, the model can be used to assess the impact of new technologies and also the timing of their adoption, on overall fleet performance and emissions.

These implications suggest that the MaritimeGCH model can be a valuable tool for both industry stakeholders, companies, and policymakers in assessing the complex challenges of decarbonizing the maritime sector while maintaining economic viability. As mentioned, no model is perfect and can answer every question, so we have made MaritimeGCH publicly and freely available, open to the community to further improve it (open-source code) and use it for similar applications in the future.

Code Availability: The model's script along with indicative datasets are publicly available at GitHub: https://github.com/Alamanos11/MaritimeGCH

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