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Keywords: shipping, GHG emissions, environmental effect

JEL Codes: L91, L92

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Abstract

To reduce greenhouse gas emissions from transport, the International Maritime Organization has been studying measures to be implemented in the short term. The present work presents an assessment of cost and environmental outcomes from the implementation of mandatory reductions of speed on the world merchant ship fleet. Considering the product usually transported by each group and the distance navigated between ports, average values of capital, operational, voyage expenditure and CO_2 emissions are calculated. Results reveal that capital and operational expenditure increase with speed reduction while voyage expenditure and CO_2 emission decrease. The effect is different for each region and ship type, whereby a given speed reduction is more beneficial for some than for others. Higher speed reductions were found to be environmentally beneficial but significantly increased the annual seaborne transport cost, which would likely affect ocean-going commerce.

Keywords: shipping, ship speed, ship power, greenhouse gas, economical effect, environmental effect

1. Introduction

Global average temperature was 1 °C higher in 2018 compared with the pre-industrial age. This temperature rise is likely to reach 1.5 °C between 2030 and 2052 if it continues to increase at the same rate [1]. Global warming is partially caused by greenhouse gas (GHG) emissions and burning of fossil fuels in the transport sector is one of the main contributors to GHG emissions. In that sector, carbon dioxide (CO_2) accounts for over 97% of the total GHG emission. Maritime transport is responsible for generating over 1.0 Gt of CO_2 per year, accounting for about 3% of

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global GHG emissions. Almost all this emission is due to international long-haul shipping [2, 3] and this amount is comparable to the total emissions of countries like Germany and Japan [4].

In this context, in April 2018 the International Maritime Organization (IMO) set an initial strategy for reducing GHG emissions from merchant ships. The short-, medium- and long-term candidate measures initially approved by the IMO will be under review and debate over the next years so that a more solid and definitive strategy can be implemented from 2023 onwards. Despite being an important step toward mitigating climate change, the guidelines of the new IMO strategy [5] should be carefully analyzed. Long-haul shipping is an extremely efficient and cost-effective mode of interchange [3], which can play an important role in technology transfer between different regions of the world, including emission reduction technologies, especially in highly mitigated scenarios [6].

One of the goals of the IMO's initial strategy is an absolute reduction of at least 50% of the annual CO_2 emission by 2050 compared to 2008. Setting such a target could lead to a significant reduction of the mentioned potential for technology transfer, possibly damaging other economic sectors. This restriction could even lead to productivity losses if the most appropriate factors of production cease to be used due to cost increases in international maritime transport. The initial strategy also emphasizes the importance of performing a cost-effect analysis before adopting each measure.

To compose the candidate measures for mitigating climate change, 37 proposals were submitted to the 74^{th} session of the IMO's Marine Environment Protection Committee (MEPC 74). Many of the proposals focus on energy efficiency measures and three of them are very specific in recommending speed optimization and speed reduction mechanisms. A careful impact assessment must precede the implementation of the candidate measures to mitigate unexpected outcomes. Either service speed or propulsion power reductions can pose sizeable impacts on the international competitiveness of countries that are large exporters of low-value commodities (iron ore, oil, soybeans, etc.). To quantify such impacts, it is necessary to place the measures in a broader perspective by using an econometric model of partial equilibrium, for instance.

1.1. Literature review

The technical work on ship speed optimization is rather old and was mainly devoted to the tradeoff between fuel economy through ship speed reduction and the increasing fixed costs caused by longer average voyage time, [7, 8]. These surveys gained importance at the beginning of the last decade, depending on the development of environmental concerns in all economic sectors, as can be seen in [9, 10, 11, 12].

According to Ferrari et al. [13], the academic work related to slow steaming can be grouped as follows: (i) analysis of the economics drivers which encourage ship owners to practice voluntary ship speed reduction aimed at reducing voyage costs; (ii) investigation of the impacts to shipping operations from the use of the slow steaming relating to service patterns or speed and fleet optimization; (iii) studies related to engine efficiency or ship design involving technology assessments of widespread use of this strategy; (iv) analysis of the regulatory domain of slow steaming, and finally; (v) examination of the environmental impact of adopting slow steaming. Ferrari [13] pointed out that although most contributions focus on a limited research theme, sometimes, a single study includes more than one of these approaches.

Psaraftis and Kontovas [14] carried out a very extensive classification of speed models for energy efficiency in maritime transport and underlined the need for a careful assessment with a view to the adoption of compulsory ship speed reduction. This measure can cause increasing CO_2 emissions by shipbuilding and scrapping activity (sectorial carbon leakages), due to the need for more ships to meet transport demand, as well as increasing inventory costs due to additional voyage duration.

As seen previously, even though the diversity of works about slow steaming has grown, the topic of maritime transport emissions in connection with international trade is still lacking in academic and scientific studies. A notable exception is Cristea et al [15], who evaluated the international trade and greenhouse emissions from international freight transport by air, sea, rail and truck. They pointed out that the comprehension of interactions among international trade, transportation and emissions could be very useful in environmental policymaking.

1.2. Background knowledge on slow steaming

Deliberately operating at a sailing speed that is significantly lower than the maximum design speed is a practice known as slow steaming. This practice is being adopted by carriers to reduce fuel consumption and the corresponding emissions, as well as VOYEX costs and available/idle capacity in the market. The market conditions resulting from the 2008 financial crisis led to the widespread practice of slow steaming in transoceanic shipping. Even after the crisis, many companies chose to further pursue this strategy in an attempt to mitigate the negative environmental effects of shipping [16].

Slow steaming has helped shipping companies to improve their performance, along with reducing their carbon footprints, but also has some drawbacks. While on the one hand slow steaming reduces VOYEX, on the other hand the additional maritime transport capacity needed to maintain the same world trade level increases the fixed CAPEX and OPEX costs [16]. The continuous use of slow steaming may harm the main engine and certainly increases maintenance costs [17]. Moreover, engineers have to be instructed about additional routines and inspections of the main engine, which is operating outside its designed optimal range. Marine engineers have always been advised by engine manufacturers that low load operation must be avoided so that the numerous components of the engine can operate in their design range.

In short, slow steaming leads to increased fouling and deposits that deteriorate the performance of engines and auxiliary machinery, decreasing efficiency and increasing the risk of failure and even fire [17]. This requires more frequent inspections to keep operation safe, so maintenance costs grow. Furthermore, in the case of two-stroke engines, the auxiliary blowers and auxiliary steam boilers have to be in service to boost the performance of turbochargers and exhaust gas boilers. This represents an additional fuel cost since the auxiliary engines must generate power to the blowers and the auxiliary steam boilers consume fuel [18]. These issues reinforce the need for an economic study of the impact of implementing a mandatory speed reduction for the world marine fleet.

1.3. Aim and structure of the paper

The present work aims to develop an approach to estimate the environmental gain from lower CO_2 emissions and the economic impact of implementing a mandatory reduction of speed and propulsion power for the world marine fleet. This bottom-up analysis comprises the estimation of the ship costs and CO_2 emissions for the most significant maritime trade routes, taking into account the nature of cargo shipped and the ship type and size. This is performed by a quantitative assessment of the variation in CO_2 emissions, ship CAPEX, OPEX and VOYEX for ten scenarios of speed and power reduction. CAPEX is the costs to acquire the vessel (new or a used). OPEX is the expense involved in the day-to-day running of the ship, such as the costs of crew wage, stores, and maintenance (including periodic dry-docking). The CAPEX and OPEX of ships tend to be regarded as fixed costs, i.e., these costs are incurred irrespective of whether the vessel is operating or off-hire. On the other hand, VOYEX represents the variable costs associated with a specific voyage including items like bunker, port and canal charges.

To achieve this purpose, we mainly rely on data derived from international databases related to the international trade and the shipping industry. The model proposed calculates the quantity of CO_2 emissions and the shipping costs by trade route and assesses the effect of mandatory reduction of speed and propulsion power.

The paper is structured as follows: Section 2 presents the methodology, including a flowchart of the proposed approach, the databases, aggregation operators to facilitate the template calculations and description of the main workflow. Section 3 presents the model results and discussion, including the suitability of the proposed approach, the main outcome of CO_2 emissions, as well as the annual global seaborne export transport costs. Section 4 presents our final conclusions.

2. Methodology

Figure 1 presents an overall flowchart of the proposed approach. The main workflow of the approach is surrounded by dotted lines and consists of exploring a database and performing six processes to obtain the outputs. The main workflow starts with a trade database of pairwise exports of quantities sorted by product and regional aggregation operators. The next processes, from 1 to 5, are used to enrich the export flow data with the required information to allow proper assessment of the model's outputs. Process 6 refers to the computation module, which reads the data and the simulation matrix to make the above-mentioned assessment. Secondary workflows related to the world merchant fleet, distances between ports and also costs, besides other databases, processes and aggregation operators, are used to feed the main workflow.

All the databases, documents, datasets, processes and aggregation operators are detailed next.

2.1. Databases

Here we discuss all the databases consulted during the execution of the present work. The base year used for all the time-dependent data was 2018, except when otherwise stated.

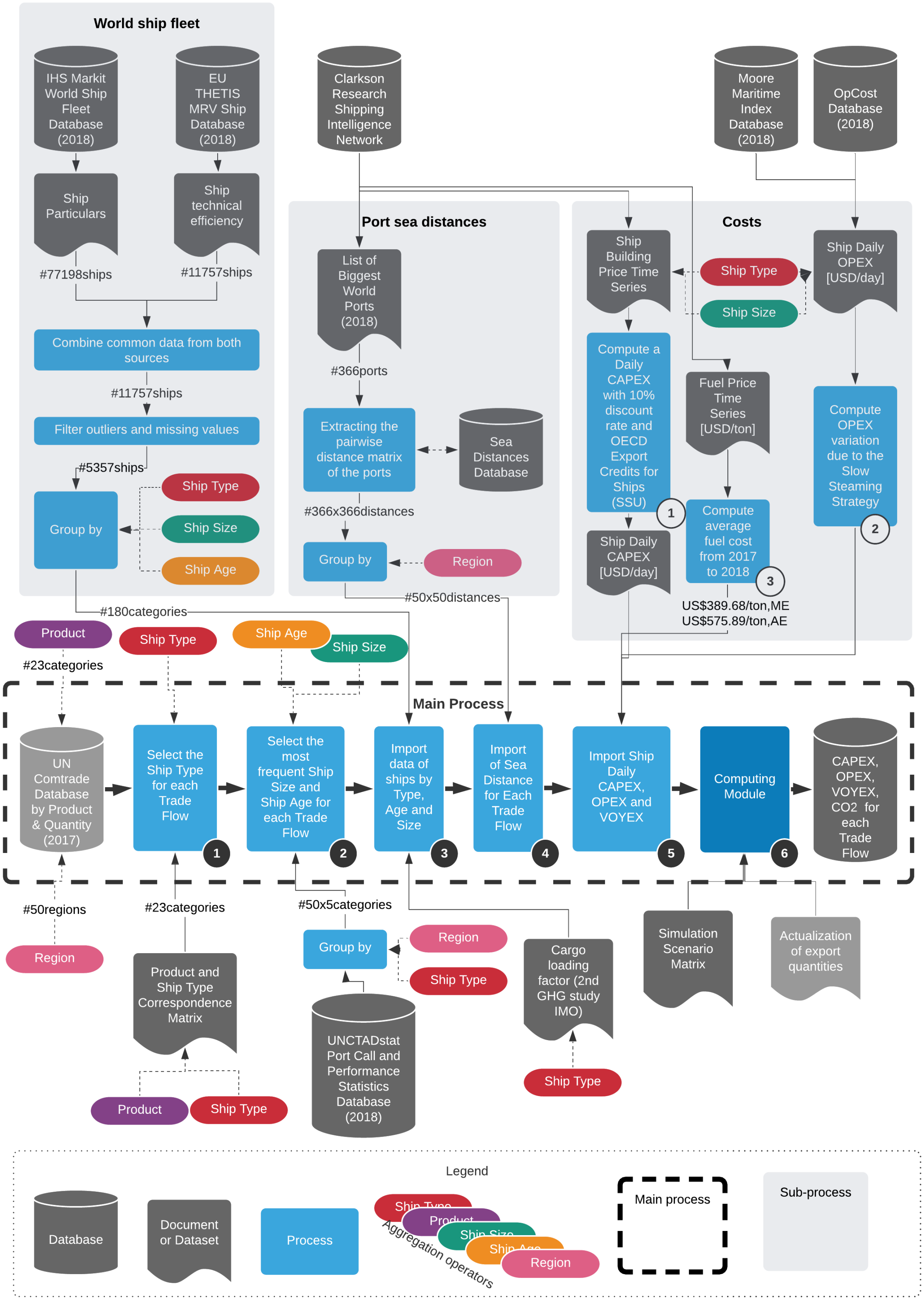


Figure 1: Flowchart of the developed approach.

2.1.1. *IHS Markit Sea-Web – World Ship Fleet Database*

The IHS Markit Sea-Web service (`https://maritime.ihs.com/`) is one of the largest maritime databases available, covering ship characteristics, movements, ports, terminals and berths, among others. Here we used the world maritime fleet product of the IHS Markit Sea-Web service to obtain the vessel particulars of the global seagoing ship fleet; around 77,198 ships. Figure 2 shows the quantity of available data for the fields that were used. Noticeably, some important information is lacking, such as the fuel consumption of the main and auxiliary engines, installed power of auxiliary engines, among others. This must be taken into account in validating the approach.

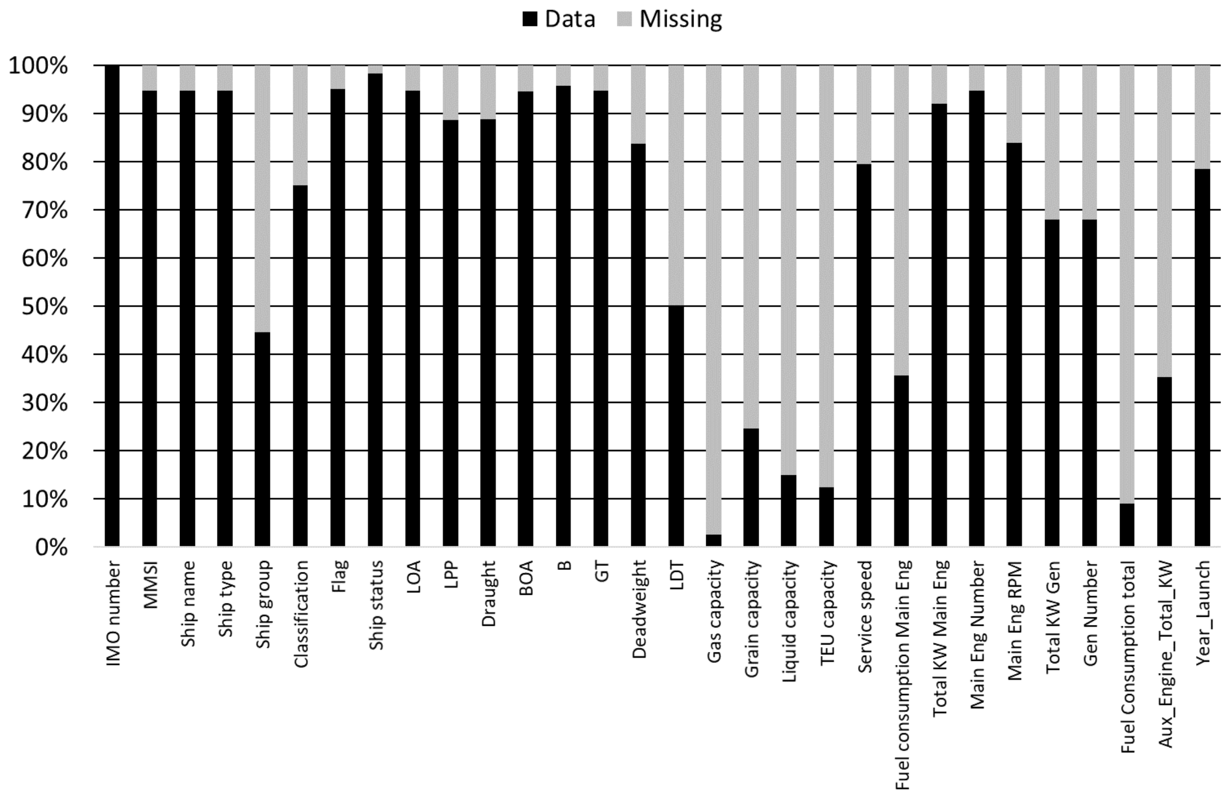


Figure 2: Available and missing data from the IHS database.

2.1.2. *EU THETIS MRV Ship Database*

The EU THETIS MRV Ship Database is an online spreadsheet (`https://mrv.emsa.europa.eu/#public/emission-report`) available solely for the information regarding Article 21 of Regulation (EU) 2015/7572 (`https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02015R0757-20161216`) on the monitoring, reporting and verification (MRV) of carbon dioxide emissions from maritime transport. This Regulation applies to ships above 5000 GT in respect of CO_2 emissions released during their voyages in which at least one of the ports is under the jurisdiction of an EU Member State. All emission data are entered by companies and confirmed by verifiers accredited by EU Member States' National Accreditation Bodies. The database contains 11757 vessels (accessed in December 2019).

2.1.3. Clarksons Research Shipping Intelligence Network

Clarksons Research (`https://www.clarksons.net/portal`) is one of the main providers of integrated shipping services. Its Shipping Intelligence Network (SIN) dataset contains access to a comprehensive range of data, such as market reports, fleet, data and time series of key market and commercial indicators. From this dataset we composed a list of the 366 most relevant seaports in the world. The location of these ports is shown in Fig. 3. The top exportation seaports were classified by product type and throughput. The TEU throughput was used for container ports, the dry bulk tonnage for iron ore, coal and grain terminals and the volume of crude oil and refined products for the oil terminals, respectively. The seaport terminals for gas and chemical products were also considered.

Figure 3: Seaports considered in the present study.

To compute the CAPEX of the vessels, the average new ship price per type and size was obtained from the SIN time series between 2017 and 2019. The SIN time series was also used to compute the average price of high-sulfur fuel oil (HSFO) 180cst with 3.5% sulfur and marine gas oil (MGO) in Singapore between 2017 and 2019. Thus, the values of USD 389.68 per ton for HSFO and USD 575.89 per ton for MGO were used.

2.1.4. Moore Maritime Index Database

The Moore Maritime Index (MMI) is a statistical database on operating costs and revenues of more than 1500 vessels (https://www.moore-index.com/). The data are extracted from the financial statements of ship-owning companies audited by Moore Global member firms and from verifiable independent submissions around the world. Information is gathered by key maritime sectors, namely, dry bulk, tanker, container and also specialized vessels, such as gas carriers.

2.1.5. OpCost Database

OpCost (https://www.opcostonline.com/) is a vessel operating cost benchmarking database created by and exclusively for BDO Shipping & Transport Group. The database provides unique information that allows ship owners, financiers, lawyers and other interested parties to benchmark vessels' operating costs against a global sample. OpCost contains data on more than 3000 vessels, grouped into dry bulk, tanker, container, offshore vessels and others.

2.1.6. Sea Distances Database

The sea distances database is an online tool (https://sea-distances.org/) containing seagoing distances between international seaports. The database consists of more than 4000 seaports and 4,000,000 pairwise sea voyage distances. The online system returns the distances in nautical miles for direct routes or passing through/around the Panama Canal, Strait of Magellan, Cape Horn, Suez Canal or Cape of Good Hope. After the extraction of the pairwise distances between the important ports, we applied a grouping algorithm by regions. This algorithm first selects the minimum sea distance for each pair of seaports. Then, the average of the distances is calculated between the two regions (several important ports and terminals in each region). A deficiency of the model presented here concerns the fact that the minimum sea distance is chosen for each pair of seaports. An improvement intended for future work is to consider other routes involving the Panama Canal, Suez Canal and others, depending on the vessel size.

2.1.7. UNCTADstat - Port Call and Performance Statistics Database

The United Nations Conference on Trade and Development (UNCTAD) makes available the statistical database called UNCTADstat. This database offers ready-to-use analytical groupings, with unique coverage for countries and products and a focus on developing and transition economies. This approach ensures data consistency across multiple data series and enables users to harness its full potential by mixing and matching data from various domains. Here, we used the maritime transport table relating to "port call and performance statistics: number of arrivals, time spent in ports (median), vessel age and size" (https://unctadstat.unctad.org/wds/ReportFolders/reportFolders.aspx?sCS_ChosenLang=en).

The aggregated figures are derived from combining information from automatic identification systems (AIS) with port mapping intelligence by Marine Traffic (http://marinetraffic.com). Only arrivals are considered to measure the total number of port calls. To produce any measurement, there must be at least 10 arrivals at a country level per commercial market made by at least 5 distinct vessels as segmented. Passenger ships and RO/RO ships are excluded from the time at port calculations. The data are gathered in 8 different markets for each country: passenger ships, wet bulk carriers, container carriers, dry breakbulk carriers, dry bulk carriers, RoRo vessels, LPG carriers and LNG carriers.

2.1.8. UN Comtrade Database by product and quantity

The United Nations Commodity Trade (UN Comtrade – https://unstats.un.org/unsd/trade/default.asp) dataset is a product collected and maintained by the United Nations Statistics Division (UNSD). It collects, compiles and disseminates detailed trade data by commodity category and by the trading partner for merchandise trade. The UN Comtrade data dissemination system offers free access to official trade statistics as reported by countries/regions. The database used here contained 42490 records of the exportation of merchandise from/to a region for each type of product category. We used 2017 has the base year instead of 2018 for the sake of completeness and quality of the data.

2.2. Documents and datasets

To perform the present work, some documents were consulted and datasets were derived from the databases. The following subsections identify these information sources.

2.2.1. Product and ship type correspondence matrix

For each of the product categories based on the UN Comtrade Database (Sec. 2.1.8), a corresponding ship type was adopted, such as listed in Tab. 1. This correspondence was formulated by minimizing the matching errors, but some inconsistencies unavoidably occurred. Some sub-products included in the processed agriculture category correspond to live animals, which are usually transported in specific livestock carriers. Due to the lack of information on these specific carriers, all the category was associated with container carriers. Transport of motor vehicles also was associated with container carriers because the model does not consider Roll-on Roll-off and pure car carriers (PCC) due to lack of information.

2.2.2. Ship cargo loading factor

The ship cargo loading factor (*LF*) takes into account that the capacity of ships is ordinarily not used in full. The values considered here were those presented in the main report of the 2^{nd} GHG emission study ordered by the IMO (https://www.transportmeasures.org/en/wiki/manuals/sea/load-capacity-utilisation/), as listed in Tab. 2. These factors refer to round-trip cycles. Moreover, for container carriers, there is also the utilization of the container itself, which is not included in this table. Hence, a container utilization factor of 0.68 was adopted. This value was estimated considering that a total of 11 billion tons was transported in 2018 while 793.26 million TEUs were handled in container port terminals worldwide [19]. This produces an average weight of 13.86 tons per TEU. Considering that a 20-foot container has a full capacity of 20 tons and an average cargo weight of 13.86 tons, the container utilization factor obtained was 0.68.

2.2.3. *Simulation scenario matrix*

The present study aims to compare a reference economic and environmental scenario with hypothetical ones where various speed and power reductions were imposed for all the ships in the world fleet. Table 3 lists the five scenarios of service speed reduction and the five scenarios of propulsion power reduction besides the reference one. In the reference scenario, the world fleet navigates at its design speed depending respectively on the vessel type, size and age. In the hypothetical scenarios, a prescriptive percentage reduction is uniformly imposed on the world fleet.

2.3. *Aggregation operators*

The five aggregation operators used here to reduce the size of the problem so that seaborne transportation of loads can be simulated are detailed next.

2.3.1. *Region*

To reduce the size of the simulation model, the world countries were gathered in 50 different regions. A region can be a country, or several countries grouped depending on the relative export quantity carried by seaborne transport. Table 4 presents the list of the 50 considered regions with the corresponding exportation in tons during 2017. The major players for export by seaborne transportation are Australia, China, Russia, Brazil, USA and E-SE-Asia, together accounting for approximately 50% of the quantity during 2017. To be able to aggregate the results at an upper level, the regions were grouped by macro-regions (MR) as follows: North America (NA), South America (SA), Europe (EU), Africa (AF), Asia (AS), Oceania (OC) and Brazil (BR). Brazil was considered separately of South America due to our particular interest.

2.3.2. *Product*

Table 5 lists the product ID of every category used in this study (the same as in Tab. 1), with the respective quantity transported in 2017. One can see that minerals, oil, coal products, processed and bulk agriculture account together for more than 80% of the quantity of the goods transported by sea.

2.3.3. *Ship type, size and age*

Only 6 ship types were considered. Each type of ship was categorized in several size ranges as shown in Tab. 6 The unit corresponding to the size of the ship depends on the ship type: deadweight (DWT) for bulk carriers, oil tankers and chemical carriers; TEU for container carriers; and cubic meters (m^3) for liquefied gas carriers. Each ship type was also categorized in five age ranges: 0-4 years, 5-9 years, 10-14 years, 15-19 years and 20 or more years.

2.4. *Main workflow*

In the main workflow, process 1, consists of assigning single ship type to each seaborne export flow occurring between each region defined in section 2.3.1. This choice was made based on the correspondence matrix between product type and ship type detailed in section 2.2.1. Process 2 selects, based on statistical data of port calls (Sec.

2.1.7), the most frequent ship size and age for each type of vessel associated with each trade flow. Therefore, the model is able to mimic the average behavior of the market, such as the use of bigger ships in the mega ports in China or the use of older ships in Africa and South America. Process 3 selects the relevant average ship data (daily fuel oil consumption, propulsion power, design speed, deadweight, etc.) for each combination of ship type, size and age. In this process, the cargo loading factor is also attributed to each ship type. Thus, it is possible to assess the average capacity per ship and the average number of required voyages per year to transport the quantity of export trade flows. Process 4 consists of importing the corresponding sea distances between the considered regions. In process 5, the daily expenditures are imported into the database according to the selected type and size of ship. Finally, process 6 involves reading the data from the simulation matrix and the database, constructed with the previous processes, and performs the simulation.

To obtain the main outputs of the model, which are the annual averages of CAPEX, OPEX, VOYEX and CO_2 emissions for each export flow, the mathematical relationships described in the next section were used.

2.4.1. Relationship between brake power and service speed

According to the propeller law [20], propeller delivered power is proportional to the cube of its rotational speed. Considering all the efficiencies over the propulsion chain as constants, brake power (P_B) is proportional to propeller delivered power. Additionally, because service speed (v_S) is proportional to propeller rotational speed, P_B is proportional to the cube of v_S. Thus, every change in brake power or service speed was correlated as in Eq. 1, where the subscripts i and o stand for input and output data, respectively.

$$\frac{P_{B,o}}{P_{B,i}} = \left(\frac{v_{S,o}}{v_{S,i}}\right)^3 \tag{1}$$

2.4.2. Relationship between fuel consumption and service speed

With the specific fuel consumption of prime movers as a constant, every change in brake power leads to a linearly proportional change in the mass flow rate of fuel [20]. Thus, the correlation between the service speed and the consumed mass flow rate of fuel can be obtained by Eq. 2.

$$\frac{\dot{m}_{f,o}}{\dot{m}_{f,i}} = \left(\frac{v_{S,o}}{v_{S,i}}\right)^3 \tag{2}$$

2.4.3. Technical efficiency equations

The technical efficiency (TE) is a measure of CO_2 emission per transport work, as defined in Eq. 3. In this equation, C_F is a dimensionless conversion factor between fuel consumption and CO_2 emission based on fuel carbon content. The ship capacity is the deadweight tonnage (DWT), except for container ships, whose capacity is taken as 70% of DWT due to the containers own weight [21]. To correlate TE with service speed (v_S) Eq. 2 is used inside Eq.

3. Then, with C_F and capacity as constants, Eq. 4 is obtained. Moreover, by combining Eq. 4 and Eq. 1, also with C_F and capacity as constants, Eq. 5 is obtained to correlate brake power (P_B) and TE.

$$TE = \frac{C_F \cdot \dot{m}_f}{capacity \cdot v_s} \tag{3}$$

$$\frac{TE_o}{TE_i} = \left(\frac{v_{s,o}}{v_{s,i}}\right)^2 \tag{4}$$

$$\frac{TE_o}{TE_i} = \left(\frac{P_{B,o}}{P_{B,i}}\right)^{2/3} \tag{5}$$

Equation 3 is also applied to compute the technical efficiency portion of to the auxiliary engines (TE_{AE}), but Eq. 4 and Eq. 5 are valid only for the main engine. In the absence of information on auxiliary engine fuel consumption (Fig. 2), an alternative approach was used. Equation 6 shows the computation of fuel by the product of auxiliary engine power (P_{AE}) and specific fuel consumption (SFC_{AE}). Auxiliary engine power is approximated by Eq. 7, depending on the maximum continuous rating (MCR) magnitude of the main engine, and specific fuel consumption is assumed to be 215 g/kWh [21]. Since we found no correlation between auxiliary power and ship speed in the literature, TE due to auxiliary engines is kept constant. Thus, the total technical efficiency (TE_t) is obtained by summing the main engine technical efficiency (TE_{ME}) and auxiliary engine technical efficiency (TE_{AE}), as in Eq. 8.

$$\dot{m}_{f,AE} = P_{AE} \cdot SFC_{AE} \tag{6}$$

$$\begin{aligned} P_{AE} &= 0.025 \cdot MCR_{ME} + 250 \\ &\qquad \text{for } MCR_{ME} \geq 10,000 \text{ kW} \\ P_{AE} &= 0.05 \cdot MCR_{ME} \\ &\qquad \text{for } MCR_{ME} < 10,000 \text{ kW} \end{aligned} \tag{7}$$

$$TE_t = TE_{ME} + TE_{AE} \tag{8}$$

The dimensionless conversion factor between fuel consumption and CO_2 emission (C_F) depends on the fuel type. Since different fuels are typically burned by the main engines and auxiliary engines, Tab. 7 lists the C_F values applied in this study (Resolution MEPC.245(66)).

It should be highlighted that two different models of technical efficiency were used in this study. The first model (M1) refers to the technical efficiency certified by the classification society and reported in the EU THETIS MRV Ship Database (Sec. 2.1.2). From there, data were grouped by ship type, size and age to obtain average values of technical efficiency for each category. The second model (M2) refers to the technical efficiency obtained through the calculation of the fuel consumption of main and auxiliary engines, as described above. A comparison between M1 and M2 is presented in the results section.

2.5. Assessment of the main outputs

The duration of a one way voyage (Δ_t) in days is given by Eq. 9, in which the distance (Δ_S) is given in nautical miles and the service speed (v_S) is given in knots.

$$\Delta_t = \frac{\Delta_S}{24 \cdot v_S} \tag{9}$$

The annual OPEX in American dollars (USD), excluding fuel-related expenditures that are classified as VOYEX, is given by Eq. 10. In that equation, n_V stands for the number of voyages a year and $OPEX_d$ is the daily operating expenditure. Analogously, the annual capital expenditure (CAPEX) and the annual voyage expenditure (VOYEX) are respectively given by Eq. 11 and Eq. 12, in which CAPEX$_d$ and VOYEX$_d$ stand for daily CAPEX and daily VOYEX. The only voyage expenditure taken into account here is that for fuel.

$$OPEX = n_V \cdot \Delta_t \cdot OPEX_d \tag{10}$$

$$CAPEX = n_V \cdot \Delta_t \cdot CAPEX_d \tag{11}$$

$$VOYEX = n_V \cdot \Delta_t \cdot VOYEX_d \tag{12}$$

The annual emission of carbon dioxide (E_{CO_2}) in tons is given by Eq. 13, in which TE stands for the technical efficiency (Eq. 3) in grams of CO_2 per tonnage capacity and nautical mile, CT is the cargo transported annually in tons and LF is the load factor.

$$E_{CO_2} = \frac{TE \cdot CT \cdot \Delta_S}{10^6 \cdot LF} \tag{13}$$

2.5.1. Daily CAPEX module

The daily capital expenditure (CAPEX$_d$) was estimated based on discounted cash flow analysis of purchase of a new vessel. The conditions used in this assessment were:

- The average new ship price from 2017 to 2019 for each ship type and size from Clarksons SIN;
- Shipping finance: OECD Export Credits for Ships (SSU);
- Finance amount: 80% of total shipyard price;
- Repayment term: 12 years after delivery;
- Interest rate: average CIRR Rates between 2017 and 2019;

- Repayments of principal and interest: half-yearly and the first payment made six months after the starting point of credit;
- Down payment of 20%, made in four installments during the construction (18 months);
- Residual value: 5% of the new price;
- Ship useful life: 20 years; and
- Discount rate: 10% per year.

The additional CAPEX resulting from the reduced ship speeds was calculated by multiplying the ship type daily capital cost by the additional voyage time at sea (pro-rata basis).

2.5.2. Daily OPEX module

The daily operational expenditure was divided into the following categories:

- Crew costs: crew wages, provisions, other crew expenses;
- Stores: lubricants, other stores;
- R&M: spares, repairs and maintenance;
- Insurance: marine insurance, P&I insurance; and
- Administration: registration costs, management fees, sundry expenses.

As explained before, these costs can be regarded as fixed when the ship is navigating at design speed. However, when significantly reducing the speed of the main engine intentionally, some of these costs may be impacted. In this study, the reduction in lubricant consumption and the increase in the main engine overhaul frequency (repair and maintenance) were considered. Consequently, we needed to find mathematical correlations between ship speed and lubricant consumption, as well as between speed and maintenance cost.

Since correlations between lubricating oil consumption (LOC) and brake power or service speed are not plentiful in the literature, the digitalization of a graph found in the literature [18] was necessary. The graph of specific cylinder oil consumption for a 4250 TEU Panamax container carrier and a normalized regression procedure led to Eq. 14, where LOC is lubricating oil consumption (mass flow rate). The correlation between brake power and LOC can be achieved by using Eq. 1 in Eq. 14.

$$\frac{LOC_o}{LOC_i} = \left(\frac{v_{S,o}}{v_{S,i}}\right)^{1/2} \tag{14}$$

Correlations for maintenance and repair costs with service speed changes were also not found in the literature. Hence, the digitalization of a graph found in [18] was again necessary. The graph relates the decreasing time between overhauls (TBO) with lower service speed due to the contamination of the fuel valve nozzle tip in a medium speed main engine. Tab. 8 was created by normalizing the data and assuming that the increase in maintenance cost is proportional to the decrease in TBO (time-based pattern). The maintenance factor was found to increase as a staircase function of the service speed ratio decrease. The correlation between brake power and maintenance cost can be found by applying Eq. 1 to the data in Tab. 8.

2.5.3. Daily VOYEX module

The daily VOYEX was estimated based only on the daily fuel oil consumption of the main and auxiliary engines multiplied by their respective fuel prices. For main engines, the average price of high sulfur fuel oil (HSFO - 180cst bunker with 3.5% sulfur) in Singapore between 2017 and 2019 was used, that is, USD 389.68 per ton. For auxiliary engines, the average price of marine gas oil (MGO) in Singapore between 2017 and 2019 was used, of USD 575.89 per ton.

As the ship service speed slows down, the rotating speed and load of the engine decline, causing a drop in exhaust gas mass flow rate. Hence, the residual energy in exhaust gases with low loads is insufficient to operate the turbocharger, so auxiliary blowers have to be put into operation. These blowers are driven by electrical motors, which means that the electricity demand increases and additional fuel is consumed by the auxiliary generation sets to feed blowers. Therefore, depending on the slow steaming level, the main engine fuel consumption decreases but the fuel consumption of the auxiliary generation sets can rise.

To establish the engine load at which blowers come into operation, the Computerized Engine Application System (CEAS), maintained by the engine manufacturer MAN (https://marine.man-es.com/two-stroke/ceas), was used. A sharp point for 35% load in the exhaust gas amount and temperature curves of two-stroke diesel engines can be noticed. Therefore, we considered that whenever engine load is less than or equal to 35%, auxiliary blowers consume additional fuel.

To find a correlation between main engine fuel consumption (m_f) and the additional auxiliary engine fuel consumption due to blowers ($m_{f,add}$), Eq. 15 and Eq. 16 were used. In the former equation, the difference between the lower calorific value taken in the catalog as reference (LCV$_{ref}$ = 42,700 kJ/kg) and the lower calorific value of heavy fuel oil (LCV$_{HFO}$ = 40,200 kJ/kg) [21] was considered. Values of specific fuel consumption and brake power for the main engine come from CEAS and are given in Tab. 9 for engine loads (EL), in which blowers are operating.

$$\dot{m}_f = \frac{SFC \cdot P_B \cdot 24}{1,000,000} \cdot \frac{LCV_{ref}}{LCV_{HFO}} \tag{15}$$

$$\dot{m}_{f,add} = \frac{SFC_{AE} \cdot P_{AE,add} \cdot 24}{1,000,000} \tag{16}$$

The additional power from auxiliary engines is estimated based on the compression power required by blowers and losses of energy in the system [20], as in Eq. 17. In this equation, m_a is the air mass flow rate, c_p is the air heat capacity (1.005 kJ/kg.K), T_d is the air discharge temperature, T_{amb} is the air ambient temperature (25 °C), η_B is the overall blower efficiency (70%), η_{ele} is the overall electric efficiency (90%), and η_{mec} is the overall mechanical efficiency (98%). Overall blower efficiency is the product of isentropic, volumetric and mechanical efficiency; overall electric efficiency is the product of generator, transformer, converter and motor efficiency; and overall mechanical efficiency is the product of shaft and gearbox efficiency. Air discharge temperature is computed based on isentropic compression by Eq. 18, where p_{sca} is the scavenge air pressure, p_{amb} is the ambient pressure (1.013 bar_a) and k is the isentropic exponent (1.4).

$$P_{AE,add} = \frac{\dot{m}_a \cdot c_p \cdot (T_d - T_{amb})}{\eta_B \cdot \eta_{ele} \cdot \eta_{mec}} \tag{17}$$

$$T_d = T_{amb} \cdot \left(\frac{p_{sca}}{p_{amb}}\right)^{\frac{k-1}{k}} \tag{18}$$

Table 9 lists the input data and outcomes of this simplified estimation for the additional fuel consumption of auxiliary generation sets due to blower operations. Although p_{sca} is supplied by CEAS from 25% engine load (EL) onwards, which means only three interesting points, a regression curve based on these data was fitted and Eq. 19 was obtained. Thus, for engine loads less than or equal to 35%, the total auxiliary engine fuel consumption is given by the sum of this value and that from Eq. 6.

$$\frac{m_{f,add}}{m_f} = 0.02573 \cdot EL^{0.6535} \tag{19}$$

2.6. Limitations of the approach

The present approach has many limitations that we intended to address in future works. The main limitations of this approach are the following:

- The nautical mile distance between a pair of seaports is estimated through the minimum navigated distance between the two seaports regardless of the ship size. This means that any ship can pass through the Panama Canal, for instance.
- Any ship may load or unload in any port regardless of the capacity (cargo type and pier/wharf capacity).
- A single ship size and age for each export trade flow is used, based on the most frequent size and age of ship calling at the ports of the considered region.
- VOYEX is represented only by the fuel costs while canal fees and port taxes are not considered.
- The same propulsion type based on fixed-pitch propeller directly driven by a slow-speed diesel engine was considered for the entire global fleet.

- Carbon leakage due to the construction of new ships to transport the same amount of merchandise per year is not considered.

- The present approach is steady-state, it does not take into account any time-dependent variation in seaborne trade.

- Economic impact of the speed and power reduction on the global trades flows are not considered in this study.

3. Results and Discussion

It is worth noting that our approach is static and does not involve any forecast for the global economy changes with time. Only the effect prescriptive uniform percentage reductions of speed and power of the world ship fleet for 2017 are considered. Thus, the next sections address the main outcomes regarding CO_2 emissions and seaborne transport costs, but, first an analysis of the proposed approach's suitability is necessary.

3.1. Suitability of the proposed approach

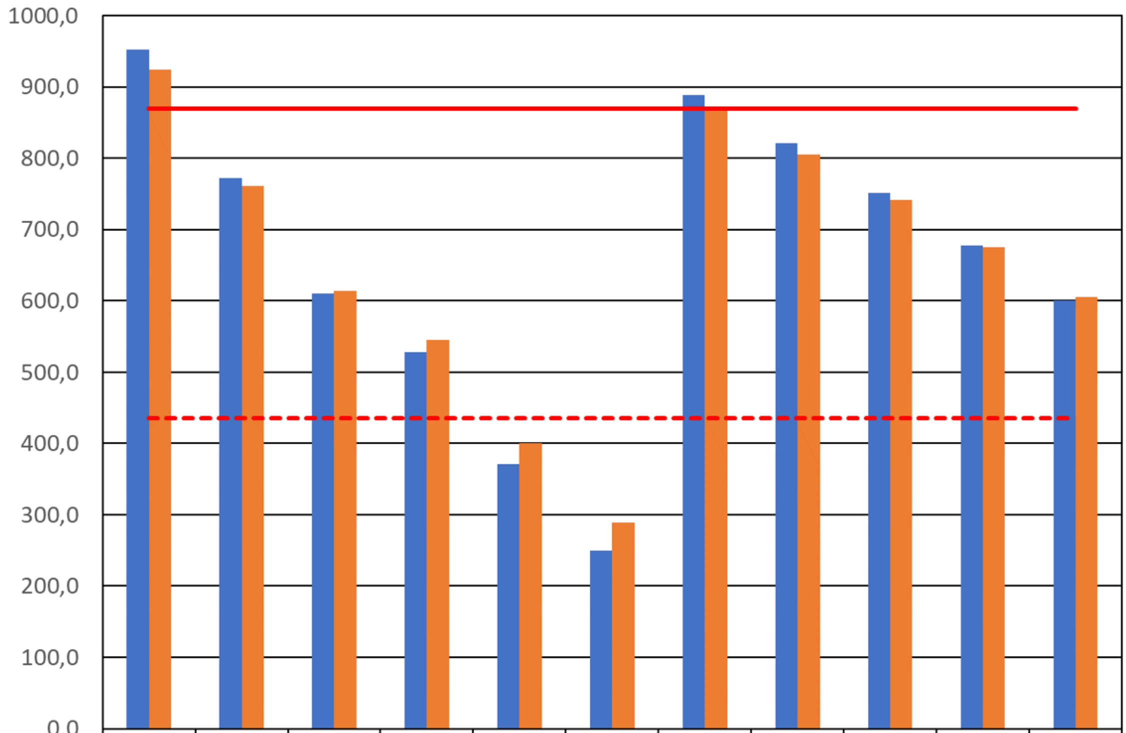
Some global outcomes of the simulation model were compared to published references to verify the suitability of the approach.

Table 10 presents a comparison of some global outcomes of the present approach to literature references. An overestimation of 23% is shown regarding the total cargo quantity transported by sea. This excess is probably transported by another transport modality. The total transport work found is closer to the value reported in the same reference, being underestimated by only 5.5%. Regarding CO_2 emission, model 1 (M1) overestimates the reference value by 12.1% whereas model 2 (M2) overestimates it by 8.8%. These emission inaccuracies can be taken as coherent since the load was overestimated as well.

Regarding the division of the cargo in the different ship types, one can see by Tab. 11 that container carriers and bulk carriers are underestimated by 32% and 29%. On the other hand, liquid cargo is overestimated. This indicates that solid cargo was probably grouped as liquid cargo in the model. However, this imbalance is mitigated when one looks at the transport work in Tab. 12. In that case, the transport work of container carriers and bulk carriers is respectively overestimated by a bit more than 6% and underestimated by 7%. The liquid cargo overestimation regarding transport work is much less than for cargo transported, being under 11%. Since the transport work division is the most important factor in the present study and takes into account the high complexity of grouping cargos, we believe these are satisfactory. Improving the matching between the products and the ship type to adjust these ratios is an improvement intended for future work.

3.1.1. The main outcome of CO_2 emissions

The two models of technical efficiency developed here gave similar results in terms of global CO_2 emissions due to international seaborne shipping, as can be see in Fig. 4. The reference case of model M1, based on the technical efficiency reported in the EU THETIS MRV ship database, returns a result about 3% higher than model M2, based on the fuel consumption of main engines and auxiliary engines. The CO_2 emission for 2008 (IMO reference level) is shown as a red full line whereas IMO target (50% reduction) is shown as a red dotted line. Therefore, one can see that there was an increment of over 5% in GHG emissions from 2008 to 2017 (REF), contrary to the reduction objective. This highlights the need to implement measures to reach the target.

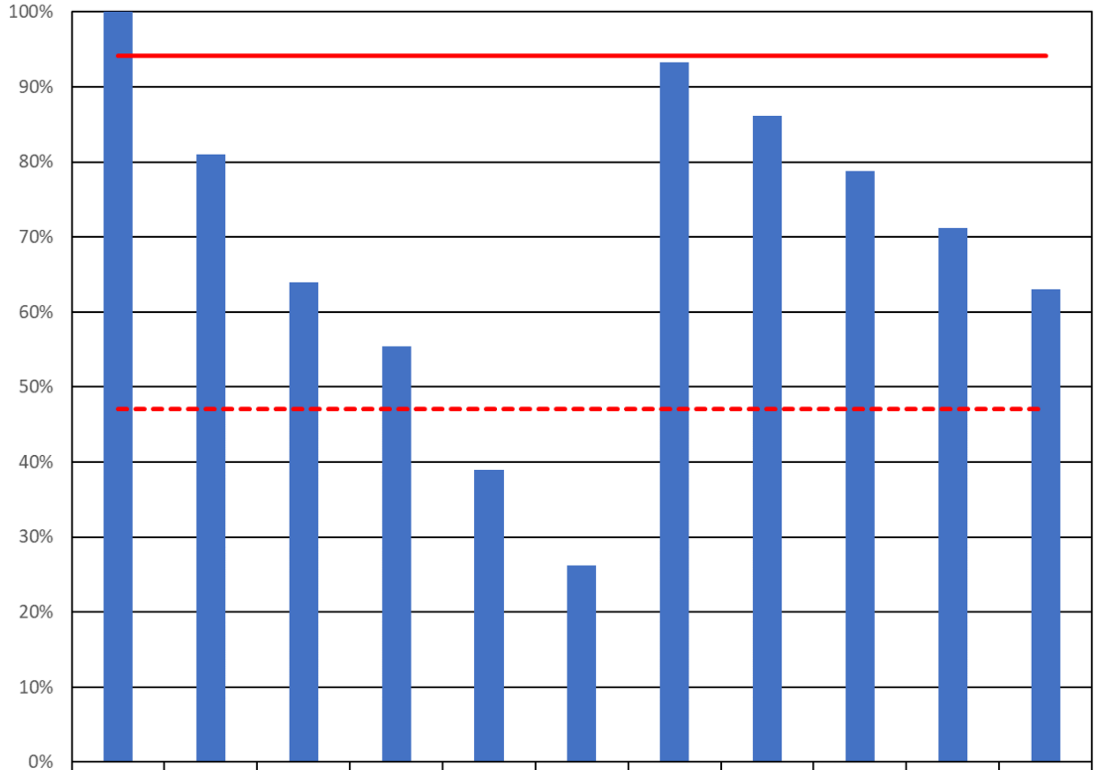


	REF	S10	S20	S30	S40	S50	P10	P20	P30	P40	P50
M1	952,8	771,8	609,8	528,1	371,5	249,7	888,2	821,1	751,2	677,8	600,3
M2	924,6	760,6	613,9	545,6	400,7	288,8	866,1	805,3	742,0	675,5	605,2
REF 2008	870	870	870	870	870	870	870	870	870	870	870
TARGET 2050	435	435	435	435	435	435	435	435	435	435	435

Figure 4: The environmental effect of slow steaming by models M1 and M2, reported in millions of tons of CO_2 for 2017.

Figure 5 shows that the higher the reduction in speed or power is, the lower the emissions generated are, and that percentage reductions of speed are significantly more effective than on power. A 50% speed reduction renders a 68% CO_2 emission reduction whereas the same power reduction renders a 34% emission reduction, compared to 2017 (REF). Hence, a prescriptive and uniform reduction of the worldwide ship fleet speed of over 30% would be required to reach the IMO target. This corresponds to a propulsion power reduction of more than 50%. The higher CO_2 emission observed for S30 and S40 in model M2 is generated by the additional power consumed by the engine blowers.

By looking at the division of CO_2 emission by ship type in Fig. 6, it can be seen that the highest contribution



	REF	S10	S20	S30	S40	S50	P10	P20	P30	P40	P50
CO2	100%	81%	64%	55%	39%	26%	93%	86%	79%	71%	63%
REF 2008	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%
TARGET 2050	47%	47%	47%	47%	47%	47%	47%	47%	47%	47%	47%

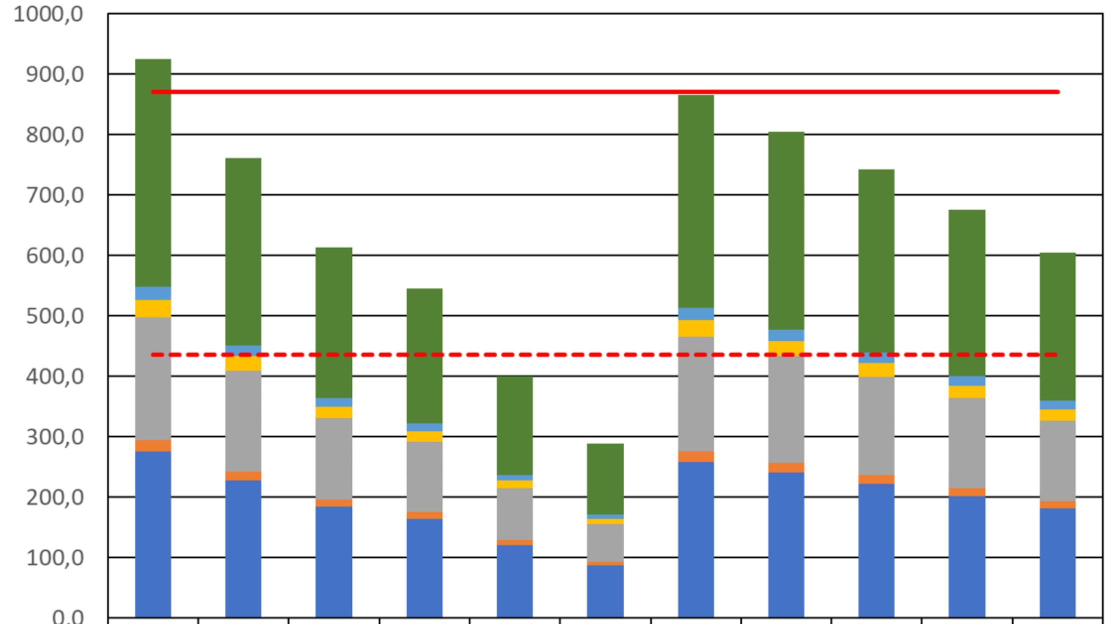
Figure 5: The environmental effect of slow steaming of model M2, reported in percentage of CO_2 emission for 2017.

comes from the oil tankers, followed by bulk carriers and then container carriers. Since each ship type is subject to a uniform percentage speed reduction, the contributions of the three main ship types become closer as the reduction increases. Therefore, with a speed reduction of 50% (S50), the contributions of oil tankers, bulk carriers and container carriers become almost the same. Given this scenario, in which those three ship types are together responsible for over 93% emissions, an alternative would be to adopt higher speed or power reductions only for the larger contributors.

Figure 7 shows the effect of the slow steaming strategy on the annual global CO_2 shipping emissions per macro-region. The main contributor is Europe (EU), followed by Asia (AS) and North America (NA). Europe represents almost 34% of the worldwide CO_2 emissions whereas those three larger contributors represent together over 77%. Brazil (BR) accounts for around 6% of the global shipping emissions whereas the rest of South America (SA) accounts for around 3%.

3.2. *Annual global seaborne export transport costs*

Figure 8 shows that as service speed or propulsion power decreases, CAPEX and OPEX grow whereas VOYEX declines. The CAPEX growth is due to the need to purchase more ships to transport the same amount of cargo per



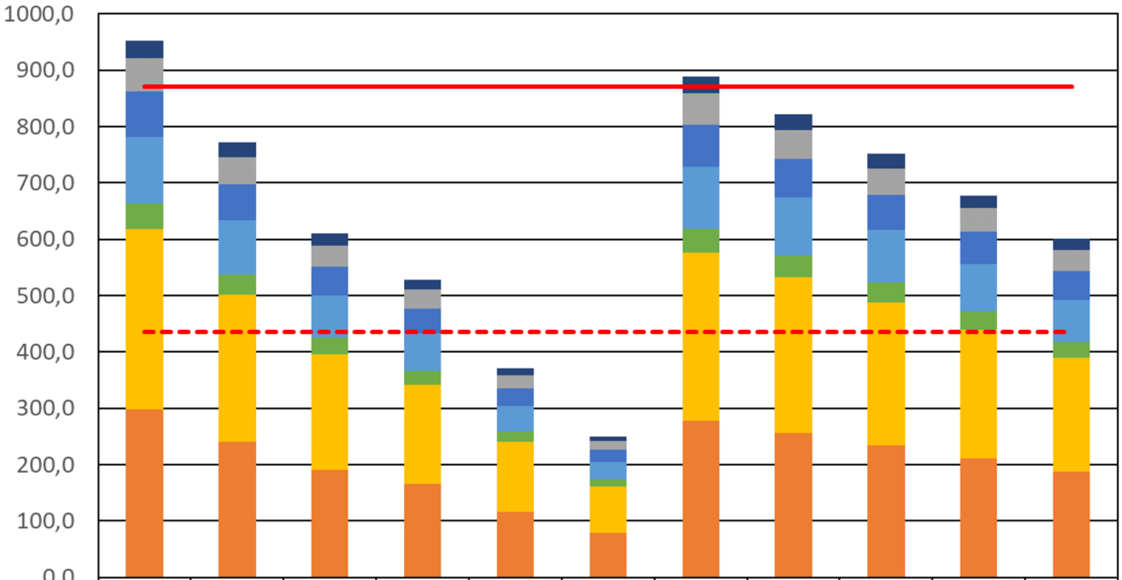
	REF	S10	S20	S30	S40	S50	P10	P20	P30	P40	P50
Oil Tanker	376,6	309,7	249,9	223,8	163,7	117,5	352,8	328,0	302,1	275,0	246,3
LPG Carrier	21,7	17,8	14,4	12,9	9,5	6,9	20,3	18,9	17,4	15,9	14,2
LNG Carrier	28,9	23,7	19,0	17,0	12,3	8,7	27,1	25,1	23,1	21,0	18,8
Container Carrier	203,3	167,3	135,0	116,6	86,6	62,9	190,4	177,1	163,1	148,5	133,1
Chemical Carrier	18,0	14,8	11,9	10,7	7,9	5,7	16,8	15,7	14,4	13,1	11,8
Bulk Carrier	276,1	227,3	183,6	164,6	120,8	87,2	258,7	240,6	221,7	202,0	181,1
REF 2008	870	870	870	870	870	870	870	870	870	870	870
TARGET 2050	435	435	435	435	435	435	435	435	435	435	435

Figure 6: The environmental effect of slow steaming by ship type, reported in millions of tons of CO_2 for 2017.

year, since loads take more time to reach the destination. The OPEX growth is due to additional costs for repairs and maintenance and also other costs that increase with the expansion of the fleet, such as crew, stores, insurance and administration costs. On the other hand, less fuel burned causes VOYEX to decrease. The total cost decreases until a speed reduction of 20% (S20) and rises from 30% (S30) onwards, rising above the reference case for 40% speed reduction (S40). This means that the growth in CAPEX and OPEX is greater than the drop in VOYEX for higher speed reductions.

As shown in Fig. 9, regarding the economic effect of slow steaming by ship type, the highest total cost comes from the oil tankers, followed by container carriers and then bulk carriers. Note that oil tankers are also the greatest contributors to emissions (Fig. 6), but container carriers and bulk carriers change positions. Although each ship type is subject to a uniform percentage speed reduction, oil tankers face a continued increase in total cost whereas the cost of container carriers decreases until 40% speed reduction (S40). The speed reduction of 50% (S50) would cause cost growth for every ship type.

Figure 10 shows the effect of the slow steaming strategy on the total annual global costs regarding macro-regions.



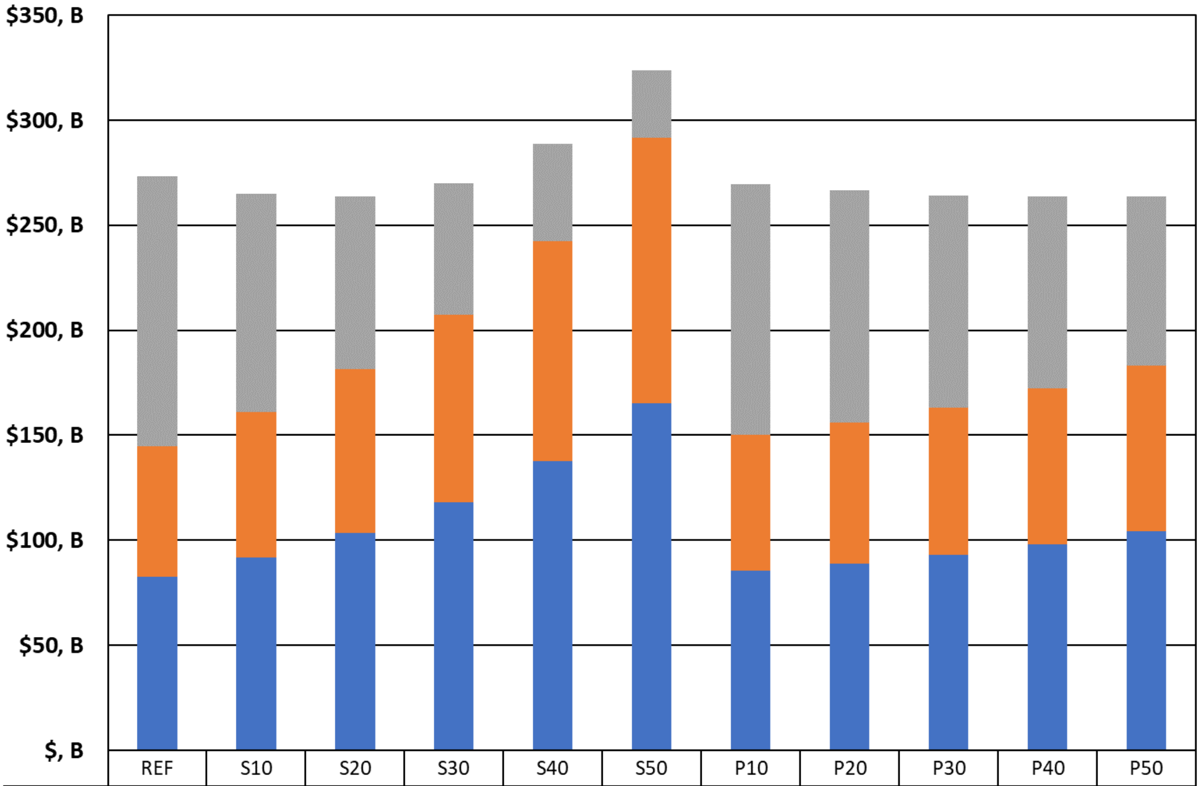
	REF	S10	S20	S30	S40	S50	P10	P20	P30	P40	P50
SA	32,2	26,0	20,6	17,9	12,6	8,4	30,0	27,7	25,3	22,9	20,3
BR	59,2	47,9	37,9	33,0	23,2	15,5	55,2	51,0	46,7	42,1	37,3
AF	79,7	64,5	51,0	44,3	31,1	20,9	74,3	68,7	62,8	56,7	50,2
NA	118,4	95,9	75,8	66,2	46,4	31,1	110,4	102,1	93,4	84,3	74,6
OC	45,2	36,6	28,9	25,5	17,8	11,9	42,2	39,0	35,7	32,2	28,5
EU	321,0	260,0	205,4	176,1	124,3	83,8	299,2	276,6	253,1	228,3	202,2
AS	297,2	240,7	190,2	165,2	116,1	78,0	277,0	256,1	234,3	211,4	187,2
REF 2008	870	870	870	870	870	870	870	870	870	870	870
TARGET 2050	435	435	435	435	435	435	435	435	435	435	435

Figure 7: The environmental effect of slow steaming by macro-region, reported in millions of tons of CO_2 for 2017.

The main contributor is Asia (AS), followed by Europe (EU) and then Oceania (OC). Notice that AS and EU changed positions and OC is a larger contributor than North America (NA) when comparing the economic scenario with the environmental scenario (Fig. 7). While a 10% speed reduction (S10) is economically beneficial for every macro-region, a 20% reduction (S20) is no longer beneficial for NA, Africa (AF) and EU. The only macro-region that always benefits from speed reductions until 40% (S40) is OC. Like for ship types (Fig. 9), the speed reduction of 50% (S50) would cause higher costs for every macro-region when compared with 40% (S40).

4. Conclusion

This work provides a quantitative assessment of cost and environmental aspects affected by the implementation of a slow steaming strategy for the world merchant fleet. The cost aspect was assessed by the total annual cost composed of capital expenditures (CAPEX), operating expenditures (OPEX) and voyage expenditures (VOYEX). In turn, the environmental aspect was assessed by annual CO_2 emissions. The world seaborne trade (exports) was used to simulate the world maritime transport network and investigate various scenarios of speed and power reductions.

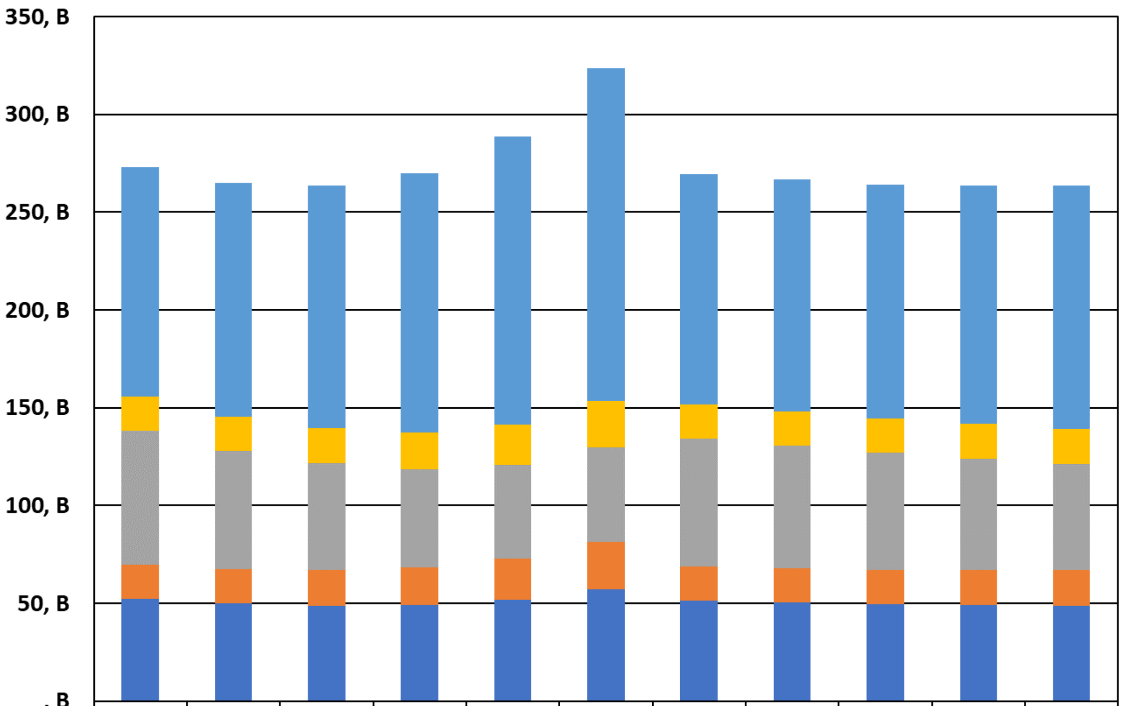


	REF	S10	S20	S30	S40	S50	P10	P20	P30	P40	P50
VOYAGE	$128,3 B	$103,93 B	$82,11 B	$62,87 B	$46,19 B	$32,08 B	$119,6 B	$110,57 B	$101,15 B	$91,27 B	$80,83 B
OPEX	$62,28 B	$69,06 B	$78,23 B	$89,19 B	$104,73 B	$126,46 B	$64,47 B	$67, B	$69,99 B	$74,27 B	$78,83 B
CAPEX	$82,65 B	$91,84 B	$103,32 B	$118,08 B	$137,76 B	$165,31 B	$85,61 B	$89,04 B	$93,09 B	$98, B	$104,14 B

Figure 8: The economic effect of slow steaming by cost category reported in billions of USD for 2017.

By examining the environmental results, one can see that higher reductions of speed or power are associated with lower emissions generated, and that speed reduction is significantly more effective than power reduction. A uniform reduction of the fleet speed of just over 30% would be required to attain the IMO's target. Since over 93% of CO_2 emissions come from only three ship types and three macro-regions are responsible for over 77% of emissions, implementing different reductions per ship type or macro-region would be reasonable alternatives.

Concerning the cost effect of slow steaming, service speed or propulsion power reduction is associated with growth of CAPEX and OPEX but decline of VOYEX. Moreover, the growth of CAPEX and OPEX is more pronounced than the drop in VOYEX for higher speed reductions. Hence, the total cost decreases for a speed drop until 20% but starts to increase afterwards, exceeding the reference case when the speed drop is 40%. Different speed reductions are beneficial for different ship types and macro-regions. Lower reductions are beneficial for most and higher reductions are beneficial for only a few. A 10% speed reduction is economically beneficial for all macro-regions and ship types whereas the 50% reduction is not beneficial at all. The only ship type and macro-region always benefited by speed reductions until 40% are respectively container carriers and Oceania.



	REF	S10	S20	S30	S40	S50	P10	P20	P30	P40	P50
Oil Tanker	117,68 B	119,26 B	124,26 B	132,75 B	147,33 B	170,45 B	117,93 B	118,55 B	119,64 B	121,85 B	124,66 B
LPG Carrier	17,44 B	17,44 B	17,92 B	18,91 B	20,75 B	23,78 B	17,4 B	17,4 B	17,47 B	17,67 B	17,96 B
Container Carrier	68,39 B	60,73 B	54,66 B	50,22 B	47,94 B	48,4 B	65,59 B	62,76 B	59,91 B	57,13 B	54,32 B
Chemical Carrier	17,63 B	17,62 B	18,08 B	19,07 B	20,9 B	23,93 B	17,58 B	17,58 B	17,64 B	17,83 B	18,12 B
Bulk Carrier	52,1 B	49,77 B	48,75 B	49,19 B	51,76 B	57,28 B	51,17 B	50,32 B	49,57 B	49,06 B	48,73 B

Figure 9: The economic effect of slow steaming by ship type reported in billions of USD for 2017.

Summarizing, a speed reduction of just over 30% would be enough to reach the target of 50% drop in CO_2 emissions in 2050 versus 2008. However, this was found without considering any time-dependent variation in global seaborne trade. Depending on the growth in seaborne trade in future years, the necessary speed reduction could be significantly different from this value. Since container carriers were found to benefit economically from speed reductions until 40%, this ship type could be prioritized for higher speed reductions. Furthermore, container carriers are in third position among those most responsible for CO_2 emissions.

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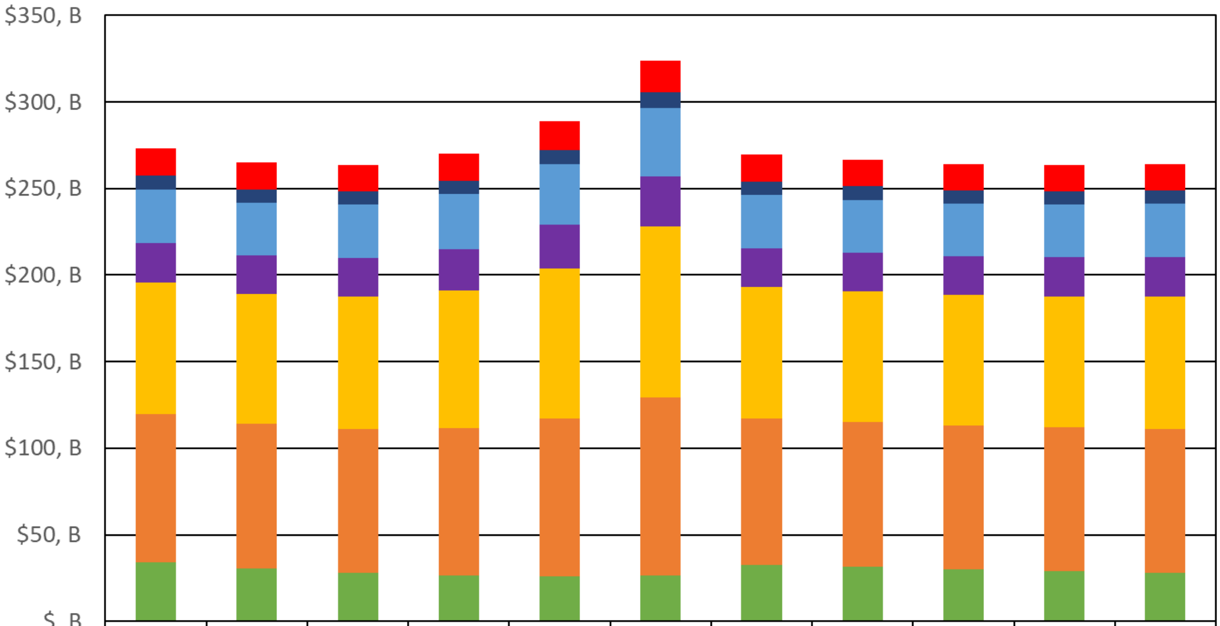

	REF	S10	S20	S30	S40	S50	P10	P20	P30	P40	P50
BR	$15,9 B	$15,35 B	$15,21 B	$15,52 B	$16,52 B	$18,46 B	$15,67 B	$15,47 B	$15,31 B	$15,23 B	$15,22 B
SA	$8, B	$7,65 B	$7,51 B	$7,58 B	$7,99 B	$8,86 B	$7,86 B	$7,74 B	$7,62 B	$7,55 B	$7,51 B
NA	$30,94 B	$30,48 B	$30,87 B	$32,14 B	$34,86 B	$39,58 B	$30,71 B	$30,54 B	$30,48 B	$30,63 B	$30,92 B
AF	$22,7 B	$22,36 B	$22,63 B	$23,56 B	$25,54 B	$28,99 B	$22,53 B	$22,4 B	$22,35 B	$22,46 B	$22,67 B
EU	$75,99 B	$75,11 B	$76,33 B	$79,73 B	$86,74 B	$98,77 B	$75,5 B	$75,19 B	$75,12 B	$75,64 B	$76,47 B
AS	$85,72 B	$83,24 B	$83,03 B	$85,23 B	$91,23 B	$102,49 B	$84,66 B	$83,75 B	$83,07 B	$82,92 B	$83,08 B
OC	$33,98 B	$30,63 B	$28,08 B	$26,37 B	$25,8 B	$26,69 B	$32,75 B	$31,51 B	$30,28 B	$29,11 B	$27,95 B

Figure 10: The economic effect of slow steaming by macro-region reported in billions of USD for 2017.

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Table 1: Products and their corresponding ship type.

ID	Product	Ship type
1	Bulk Agriculture (High Added Value)	Container Carrier
2	Bulk Agriculture (Low Added Value)	Bulk Carrier
3	Chemical, rubber, plastic products (Bulk solid)	Bulk Carrier
4	Chemical, rubber, plastic products (High Added Value)	Container Carrier
5	Chemical, rubber, plastic products (High Added Value Solid)	Container Carrier
6	Chemical, rubber, plastic products (Liquid)	Chemical Carrier
7	Electronic equipment	Container Carrier
8	Ferrous metals (Bulk)	Bulk Carrier
9	Ferrous metals (Semi-Finished)	Container Carrier
10	Fishing	Container Carrier
11	Forest Products	Bulk Carrier
12	LNG	LNG Carrier
13	LPG	LPG Carrier
14	Leather products	Container Carrier
15	Machinery and equipment nec	Container Carrier
16	Manufactures nec	Container Carrier
17	Metal products (Large)	Bulk Carrier
18	Metal products (Small)	Container Carrier
19	Metals nec (Bulk)	Bulk Carrier
20	Metals nec (High Added Value)	Container Carrier
21	Mineral products nec (Bulk)	Bulk Carrier
22	Mineral products nec (High Added Value)	Container Carrier
23	Minerals (Bulk)	Bulk Carrier
24	Minerals (High Added Value)	Container Carrier
25	Motor vehicles and parts (Parts)	Container Carrier
26	Motor vehicles and parts (Vehicles)	Container Carrier
27	Oil	Oil Tanker
28	Paper products, publishing (Bulk)	Bulk Carrier
29	Paper products, publishing (High Added Value)	Container Carrier
30	Petroleum, coal products (Liquid)	Oil Tanker
31	Petroleum, coal products (Solid)	Bulk Carrier
32	Processed Agriculture (High Added Value)	Container Carrier
33	Processed Agriculture (Live animals)	Container Carrier
34	Textiles	Container Carrier
35	Transport equipment nec	Container Carrier
36	Wearing apparel	Container Carrier
37	Wood products	Container Carrier

Table 2: Cargo loading factor for each ship type.

Ship type	Deadweight (DWT)	*LF*
Oil tanker	All	0.48
Chemical tanker	All	0.64
LPG or LNG carrier	All	0.48
Bulk carrier	0 - 10,000	0.6
Bulk carrier	10,000 - 100,000	0.55
Bulk carrier	>100,000	0.5
Container carrier	All	0.7
Chemical carrier	All	0.64

Table 3: Simulated scenarios considered.

Scenario ID	Reduction	Operating parameter
REF	-	-
S10	-10.00%	Service speed
S20	-20.00%	
S30	-30.00%	
S40	-40.00%	
S50	-50.00%	
P10	-10.00%	Propulsion power
P20	-20.00%	
P30	-30.00%	
P40	-40.00%	
P50	-50.00%	

Table 4: Considered regions, their macro-regions (MR) and corresponding export quantities (Qua.) measured in metric tons.

Region	MR	Qua. [ton]	Qua. [%]	Region	MR	Qua. [ton]	Qua. [%]
Argentina	SA	97183772	1.00%	Netherlands	EU	179095803	1.00%
Atlantic	SA	57217	0.00%	North-Africa	AF	98282725	1.00%
Australia	OC	1311281581	9.00%	Pacific	OC	8478306	0.00%
Belgium	EU	149809584	1.00%	Paraguay	SA	11038088	0.00%
Brazil	BR	667580717	5.00%	Peru	SA	46331910	0.00%
Canada	NA	324727869	2.00%	Poland	EU	48944940	0.00%
Caribbean	NA	8555591	0.00%	R-Western-Europe	EU	415137121	3.00%
Caucasus	AS	39752416	0.00%	Rest-E-Europe	EU	3623348667	26.00%
Central-America	NA	26990642	0.00%	Rest-Middle-East	AS	226415524	2.00%
Central-Asia	AS	145973441	1.00%	Rest-S-America	SA	42647198	0.00%
Chile	SA	51156185	0.00%	Russia	AS	801024034	6.00%
China	AS	1083383688	8.00%	Singapore	AS	55324824	0.00%
Colombia	SA	149140435	1.00%	South Korea	AS	187229762	1.00%
E-SE-Asia	AS	666021615	5.00%	South-Asia	AS	15049151	0.00%
Egypt	AF	17050451	0.00%	Spain	EU	121014182	1.00%
France	EU	173849979	1.00%	Sub-Saharan-Africa	AF	664186590	5.00%
Germany	EU	146045205	1.00%	Switzerland	EU	11374754	0.00%
Hong Kong	AS	16576704	0.00%	Taiwan	AS	73835182	1.00%
India	AS	204340714	1.00%	Thailand	AS	119107814	1.00%
Indian-Ocean	AS	71935	0.00%	Turkey	AS	94422523	1.00%
Iran	AS	101766905	1.00%	UAE	AS	55096383	0.00%
Italy	EU	89352316	1.00%	UK	EU	148371447	1.00%
Japan	AS	137543915	1.00%	USA	NA	795916546	6.00%
Malaysia	AS	216621681	2.00%	Uruguay	SA	4730782	0.00%
Mexico	NA	121837061	1.00%	Vietnam	AS	74718539	1.00%
				Grand Total		1,39E+10	100.00%

Table 5: Quantity transported of every product in tons.

Product ID	Quantity [ton]	Quantity [%]
1	14,791,932	0.00%
2	614,932,142	4.00%
3	403,750,938	3.00%
4	180,811,867	1.00%
5	137,441	0.00%
6	331,113,926	2.00%
7	52,736,639	0.00%
8	330,408,845	2.00%
9	157,002,458	1.00%
10	3,684,168	0.00%
11	78,399,032	1.00%
12	267,157,822	2.00%
13	227,354,304	2.00%
14	11,153,912	0.00%
15	66,433,442	0.00%
16	42,046,932	0.00%
17	19,299,690	0.00%
18	57,340,060	0.00%
19	43,440,015	0.00%
20	59,268,121	0.00%
21	180,963,293	1.00%
22	165,151,804	1.00%
23	2,347,117,067	17.00%
24	2,080,271	0.00%
25	33,444,565	0.00%
26	49,150,535	0.00%
27	1,004,682,751	7.00%
28	93,424,305	1.00%
29	101,879,621	1.00%
30	4,036,597,729	29.00%
31	1,515,523,462	11.00%
32	1,150,741,375	8.00%
33	3,638,148	0.00%
34	51,444,327	0.00%
35	35,723,102	0.00%
36	12,299,082	0.00%
37	122,669,290	1.00%
Grand total	13,867,794,414	100.00%

Table 6: Categorization of ships per type and size.

Ship type	Ship size	Unit	Ship type	Ship size	Unit	Ship type	Ship size	Unit
	10000 - 19999			100 - 999			up to 999	
	20000 - 24999			1000 - 1999			1000-1999	
	25000 - 29999			2000 - 2999			2000-4999	
	30000 - 39999			3000 - 3999		LPG Carrier	5000-9999	m^3
	40000 - 49999			4000 - 4999			10000-19999	
Bulk Carrier	50000 - 64999	DWT		5000 - 5999			20000-44999	
	65000 - 79999			6000 - 6999			45000-64999	
	80000 - 99999		Container Carrier	7000 - 7999	TEU		65000 and larger	
	100000 - 119999			8000 - 8999			up to 4999	
	120000 - 159999			9000 - 9999			5000-19999	
	160000 and larger			10000 - 11999			20000-39999	
	10000 - 24999			12000 - 13999			40000-59999	
	25000 - 39999			14000 - 14999		LNG Carrier	60000-99999	m^3
	40000 - 54999			15000 - 17999			100000-119999	
	55000 - 84999			18000 and larger			120000-129999	
Oil Tanker	85000 - 124999	DWT					130000-139999	
	125000 - 159999						140000 and larger	
	160000 - 199999							
	200000 - 319999							
	320000 and larger							
	up to 10000							
	10000 - 19999							
Chemical Carrier	20000 - 29999	DWT						
	30000 - 39999							
	40000 and larger							

Table 7: Non-dimensional conversion factor (C_F) between fuel consumption and CO_2 emission.

Machinery	Fuel type	C_F [kg_{CO_2}/kg_f]
Main engines	Heavy Fuel Oil	3.114
Auxiliary engines	Diesel/Gas Oil	3.206

Table 8: Correlation of maintenance factor with service speed ratio.

Speed ratio ($v_{S,o}/v_{S,i}$)	Maintenance factor ($cost_o/cost_i$)
≥ 0.85	1
≥ 0.70 and < 0.85	1.1
≥ 0.58 and < 0.70	1.2
≥ 0.47 and < 0.58	1.3
≥ 0.37 and < 0.47	1.4
≥ 0.27 and < 0.37	1.5

Table 9: Input data and results for additional fuel consumption of auxiliary generation sets due to blower operation.

Engine	EL [%]	P_B [kW]	SFC [g/kWh]	m_a [kg/s]	p_{sca} [bar$_a$]	m_f [ton/day]	T_d [K]	$P_{AE,add}$ [kW]	$m_{f,add}$ [ton/day]	$m_{f,add}/m_f$ [%]
5S35ME-C9.7 smallest on CEAS	35	1523	171.1	3.7	1.79	6.643	350.8	316.3	1.632	24.57
	30	1305	172.1	3.6	1.64	5.725	342.1	257.1	1.326	23.17
	25	1088	174.1	3.2	1.5	4.829	333.5	183.8	0.949	19.64
12G95ME-C10.5 largest on CEAS	35	28854	162.1	69.4	1.85	119.2	354.1	6307	32.54	27.29
	30	24732	163.1	68.2	1.68	102.8	344.5	5133	26.49	25.76
	25	20610	165.1	60.6	1.53	86.74	335.4	3667	18.92	21.81

Table 10: Comparison of global outcomes of the approach with literature references.

Parameter for comparison	Reference	Model	Error [%]
Total quantity transported [10e+6 ton]	11,230 [19]	13,868	+23.5
Total transport work [10e+9 ton ·nautical mile]	57,172 [19]	54,053	-5.5
Total CO_2 emissions [10e+6 ton]	850 [2]	M1 - 953.1	+12.1
		M2 - 924.8	+8.8

Table 11: Comparison of the shipload division between the model and the reference study [19].

Reference			Model			Error
Ship type	Ratio [%]	Total ratio [%]	Ship type	Ratio [%]	Total ratio [%]	[%]
Container carrier	25.0	25.0	Container carrier	17.0	17.0	-32.0
Bulk carrier	29.0	58.0	Bulk carrier	41.0	41.0	-29.3
Other dry cargo	29.0					
			Oil tanker	36.0		
Liquid cargo	17.0	17.0	Chemical tanker	2.0	42.0	+147.1
			LNG/LPG tanker	4.0		
Grand total		100.0	Grand total		100.0	

Table 12: Comparison of the transport work repartition between the model and the literature reference [19].

Reference			Model			Error
Ship type	Ratio [%]	Total ratio [%]	Ship type	Ratio [%]	Total ratio [%]	[%]
Container carrier	15.0	15.0	Container carrier	16.0	16.0	+6.7
Bulk carrier	29.0	57.0	Bulk carrier	53.0	53.0	-7.0
	28.0					
			Oil tanker	26.0		
Liquid cargo	28.0	28.0	Chemical tanker	2.0	31.0	+10.7
			LNG/LPG tanker	3.0		
Grand total		100.0	Grand total		100.0	