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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 CO₂ emissions are calculated. Results reveal that capital and operational expenditure increase with speed reduction while voyage expenditure and CO₂ 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, 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 CO₂ emissions are calculated. Results reveal that capital and operational expenditure increase with speed reduction while voyage expenditure and CO₂ 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.

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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 (CO₂) accounts for over 97% of the total GHG emission. Maritime transport is responsible for generating over 1.0 Gt of CO₂ per year, accounting for about 3% of

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

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

16 One of the goals of the IMO's initial strategy is an absolute reduction of at least 50% of the annual CO₂ emission
17 by 2050 compared to 2008. Setting such a target could lead to a significant reduction of the mentioned potential for
18 technology transfer, possibly damaging other economic sectors. This restriction could even lead to productivity losses
19 if the most appropriate factors of production cease to be used due to cost increases in international maritime transport.
20 The initial strategy also emphasizes the importance of performing a cost-effect analysis before adopting each measure.

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

29 *1.1. Literature review*

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

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

41 these approaches.

42 Psaraftis and Kontovas [14] carried out a very extensive classification of speed models for energy efficiency in
43 maritime transport and underlined the need for a careful assessment with a view to the adoption of compulsory ship
44 speed reduction. This measure can cause increasing CO₂ emissions by shipbuilding and scrapping activity (sectorial
45 carbon leakages), due to the need for more ships to meet transport demand, as well as increasing inventory costs due
46 to additional voyage duration.

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

52 *1.2. Background knowledge on slow steaming*

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

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

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

74 1.3. Aim and structure of the paper

75 The present work aims to develop an approach to estimate the environmental gain from lower CO₂ emissions and
76 the economic impact of implementing a mandatory reduction of speed and propulsion power for the world marine
77 fleet. This bottom-up analysis comprises the estimation of the ship costs and CO₂ emissions for the most significant
78 maritime trade routes, taking into account the nature of cargo shipped and the ship type and size. This is performed
79 by a quantitative assessment of the variation in CO₂ emissions, ship CAPEX, OPEX and VOYEX for ten scenarios
80 of speed and power reduction. CAPEX is the costs to acquire the vessel (new or a used). OPEX is the expense
81 involved in the day-to-day running of the ship, such as the costs of crew wage, stores, and maintenance (including
82 periodic dry-docking). The CAPEX and OPEX of ships tend to be regarded as fixed costs, i.e., these costs are incurred
83 irrespective of whether the vessel is operating or off-hire. On the other hand, VOYEX represents the variable costs
84 associated with a specific voyage including items like bunker, port and canal charges.

85 To achieve this purpose, we mainly rely on data derived from international databases related to the international
86 trade and the shipping industry. The model proposed calculates the quantity of CO₂ emissions and the shipping costs
87 by trade route and assesses the effect of mandatory reduction of speed and propulsion power.

88 The paper is structured as follows: Section 2 presents the methodology, including a flowchart of the proposed
89 approach, the databases, aggregation operators to facilitate the template calculations and description of the main
90 workflow. Section 3 presents the model results and discussion, including the suitability of the proposed approach, the
91 main outcome of CO₂ emissions, as well as the annual global seaborne export transport costs. Section 4 presents our
92 final conclusions.

93 2. Methodology

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

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

103 2.1. Databases

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

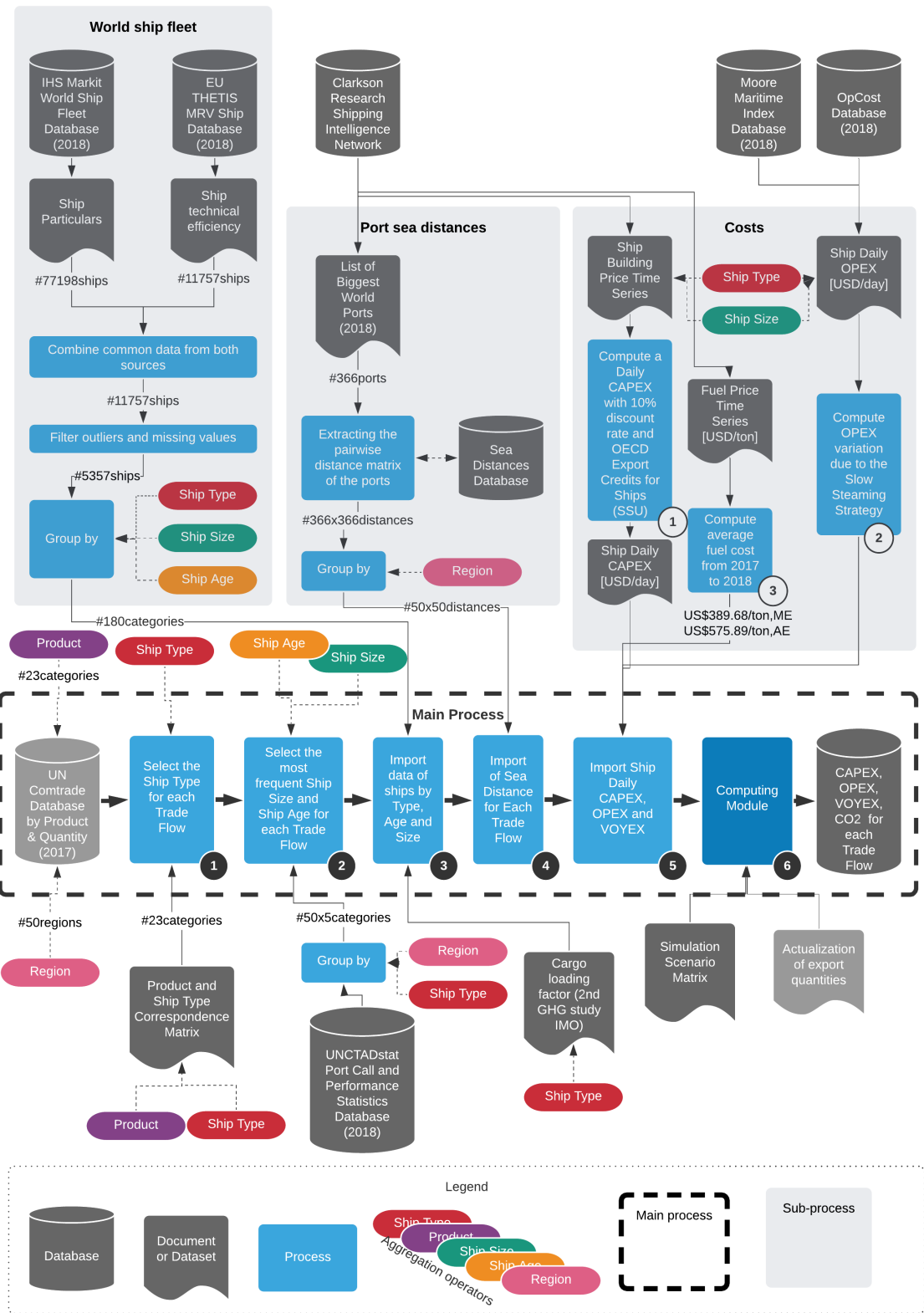


Figure 1: Flowchart of the developed approach.

106 2.1.1. IHS Markit Sea-Web – World Ship Fleet Database

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

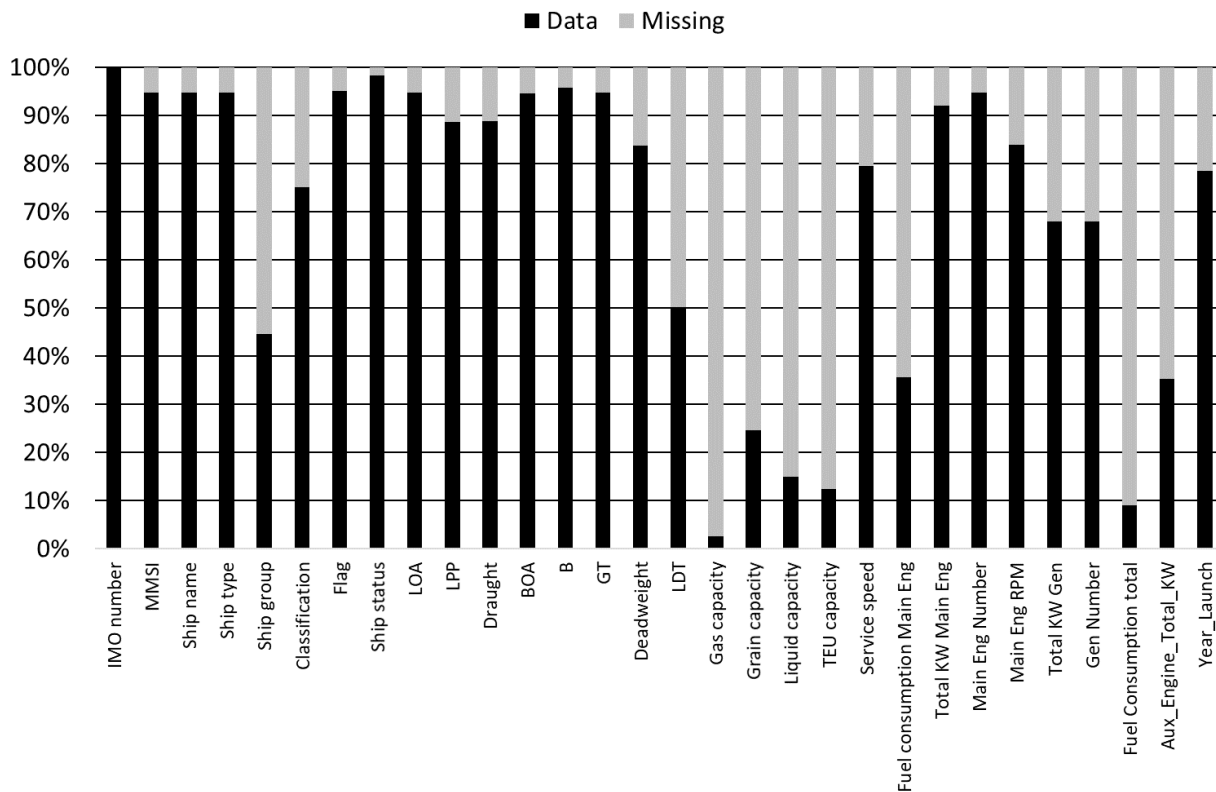


Figure 2: Available and missing data from the IHS database.

113 2.1.2. EU THETIS MRV Ship Database

114 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
 117 and verification (MRV) of carbon dioxide emissions from maritime transport. This Regulation applies to ships above
 118 5000 GT in respect of CO₂ emissions released during their voyages in which at least one of the ports is under the
 119 jurisdiction of an EU Member State. All emission data are entered by companies and confirmed by verifiers accredited

120 by EU Member States' National Accreditation Bodies. The database contains 11757 vessels (accessed in December
121 2019).

122 2.1.3. Clarksons Research Shipping Intelligence Network

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



Figure 3: Seaports considered in the present study.

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

134 2.1.4. Moore Maritime Index Database

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

140 2.1.5. OpCost Database

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

145 2.1.6. Sea Distances Database

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

155 2.1.7. UNCTADstat - Port Call and Performance Statistics Database

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

163 The aggregated figures are derived from combining information from automatic identification systems (AIS) with
164 port mapping intelligence by Marine Traffic (<http://marinetraffic.com>). Only arrivals are considered to measure
165 the total number of port calls. To produce any measurement, there must be at least 10 arrivals at a country level per
166 commercial market made by at least 5 distinct vessels as segmented. Passenger ships and RO/RO ships are excluded

167 from the time at port calculations. The data are gathered in 8 different markets for each country: passenger ships,
168 wet bulk carriers, container carriers, dry breakbulk carriers, dry bulk carriers, RoRo vessels, LPG carriers and LNG
169 carriers.

170 2.1.8. UN Comtrade Database by product and quantity

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

178 2.2. Documents and datasets

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

181 2.2.1. Product and ship type correspondence matrix

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

189 2.2.2. Ship cargo loading factor

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

199 *2.2.3. Simulation scenario matrix*

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

205 *2.3. Aggregation operators*

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

208 *2.3.1. Region*

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

217 *2.3.2. Product*

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

221 *2.3.3. Ship type, size and age*

222 Only 6 ship types were considered. Each type of ship was categorized in several size ranges as shown in Tab.
223 6 The unit corresponding to the size of the ship depends on the ship type: deadweight (DWT) for bulk carriers, oil
224 tankers and chemical carriers; TEU for container carriers; and cubic meters (m³) for liquefied gas carriers. Each ship
225 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.

226 *2.4. Main workflow*

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

230 [2.1.7](#)), the most frequent ship size and age for each type of vessel associated with each trade flow. Therefore, the
 231 model is able to mimic the average behavior of the market, such as the use of bigger ships in the mega ports in China
 232 or the use of older ships in Africa and South America. Process 3 selects the relevant average ship data (daily fuel oil
 233 consumption, propulsion power, design speed, deadweight, etc.) for each combination of ship type, size and age. In
 234 this process, the cargo loading factor is also attributed to each ship type. Thus, it is possible to assess the average
 235 capacity per ship and the average number of required voyages per year to transport the quantity of export trade flows.
 236 Process 4 consists of importing the corresponding sea distances between the considered regions. In process 5, the
 237 daily expenditures are imported into the database according to the selected type and size of ship. Finally, process 6
 238 involves reading the data from the simulation matrix and the database, constructed with the previous processes, and
 239 performs the simulation.

240 To obtain the main outputs of the model, which are the annual averages of CAPEX, OPEX, VOYEX and CO₂
 241 emissions for each export flow, the mathematical relationships described in the next section were used.

242 2.4.1. Relationship between brake power and service speed

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

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

248 2.4.2. Relationship between fuel consumption and service speed

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

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

252 2.4.3. Technical efficiency equations

253 The technical efficiency (TE) is a measure of CO₂ emission per transport work, as defined in Eq. [3](#). In this
 254 equation, C_F is a dimensionless conversion factor between fuel consumption and CO₂ emission based on fuel carbon
 255 content. The ship capacity is the deadweight tonnage (DWT), except for container ships, whose capacity is taken as
 256 70% of DWT due to the containers own weight [\[21\]](#). To correlate TE with service speed (v_S) Eq. [2](#) is used inside Eq.

257 **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
 258 and capacity as constants, Eq. **5** is obtained to correlate brake power (P_B) and TE .

$$TE = \frac{C_F \cdot \dot{m}_f}{capacity \cdot v_s} \quad (3)$$

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

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

259 Equation **3** is also applied to compute the technical efficiency portion of to the auxiliary engines (TE_{AE}), but Eq. **4**
 260 and Eq. **5** are valid only for the main engine. In the absence of information on auxiliary engine fuel consumption (Fig.
 261 **2**), an alternative approach was used. Equation **6** shows the computation of fuel by the product of auxiliary engine
 262 power (P_{AE}) and specific fuel consumption (SFC_{AE}). Auxiliary engine power is approximated by Eq. **7**, depending
 263 on the maximum continuous rating (MCR) magnitude of the main engine, and specific fuel consumption is assumed
 264 to be 215 g/kWh **[21]**. Since we found no correlation between auxiliary power and ship speed in the literature, TE
 265 due to auxiliary engines is kept constant. Thus, the total technical efficiency (TE_t) is obtained by summing the main
 266 engine technical efficiency (TE_{ME}) and auxiliary engine technical efficiency (TE_{AE}), as in Eq. **8**.

$$\dot{m}_{f,AE} = P_{AE} \cdot SFC_{AE} \quad (6)$$

$$P_{AE} = 0.025 \cdot MCR_{ME} + 250$$

for $MCR_{ME} \geq 10,000$ kW

$$P_{AE} = 0.05 \cdot MCR_{ME} \quad (7)$$

for $MCR_{ME} < 10,000$ kW

$$TE_t = TE_{ME} + TE_{AE} \quad (8)$$

267 The dimensionless conversion factor between fuel consumption and CO₂ emission (C_F) depends on the fuel type.
 268 Since different fuels are typically burned by the main engines and auxiliary engines, Tab. **7** lists the C_F values applied
 269 in this study (Resolution MEPC.245(66)).

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

276 2.5. Assessment of the main outputs

277 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
278 miles and the service speed (v_S) is given in knots.

$$\Delta_t = \frac{\Delta_S}{24 \cdot v_S} \quad (9)$$

279 The annual OPEX in American dollars (USD), excluding fuel-related expenditures that are classified as VOYEX,
280 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
281 expenditure. Analogously, the annual capital expenditure (CAPEX) and the annual voyage expenditure (VOYEX) are
282 respectively given by Eq. 11 and Eq. 12, in which $CAPEX_d$ and $VOYEX_d$ stand for daily CAPEX and daily VOYEX.
283 The only voyage expenditure taken into account here is that for fuel.

$$OPEX = n_V \cdot \Delta_t \cdot OPEX_d \quad (10)$$

$$CAPEX = n_V \cdot \Delta_t \cdot CAPEX_d \quad (11)$$

$$VOYEX = n_V \cdot \Delta_t \cdot VOYEX_d \quad (12)$$

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

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

287 2.5.1. Daily CAPEX module

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

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

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

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

303 2.5.2. Daily OPEX module

304 The daily operational expenditure was divided into the following categories:

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

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

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

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

320 Correlations for maintenance and repair costs with service speed changes were also not found in the literature.
321 Hence, the digitalization of a graph found in [18] was again necessary. The graph relates the decreasing time between

322 overhauls (TBO) with lower service speed due to the contamination of the fuel valve nozzle tip in a medium speed
 323 main engine. Tab. 8 was created by normalizing the data and assuming that the increase in maintenance cost is
 324 proportional to the decrease in TBO (time-based pattern). The maintenance factor was found to increase as a staircase
 325 function of the service speed ratio decrease. The correlation between brake power and maintenance cost can be found
 326 by applying Eq. 1 to the data in Tab. 8.

327 2.5.3. Daily VOYEX module

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

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

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

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

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

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

349 The additional power from auxiliary engines is estimated based on the compression power required by blowers
 350 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

351 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
 352 the overall blower efficiency (70%), η_{ele} is the overall electric efficiency (90%), and η_{mec} is the overall mechanical
 353 efficiency (98%). Overall blower efficiency is the product of isentropic, volumetric and mechanical efficiency; overall
 354 electric efficiency is the product of generator, transformer, converter and motor efficiency; and overall mechanical
 355 efficiency is the product of shaft and gearbox efficiency. Air discharge temperature is computed based on isentropic
 356 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
 357 isentropic exponent (1.4).

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

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

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

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

363 2.6. Limitations of the approach

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

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

- 375 • Carbon leakage due to the construction of new ships to transport the same amount of merchandise per year is
376 not considered.
- 377 • The present approach is steady-state, it does not take into account any time-dependent variation in seaborne
378 trade.
- 379 • Economic impact of the speed and power reduction on the global trades flows are not considered in this study.

380 **3. Results and Discussion**

381 It is worth noting that our approach is static and does not involve any forecast for the global economy changes with
382 time. Only the effect prescriptive uniform percentage reductions of speed and power of the world ship fleet for 2017
383 are considered. Thus, the next sections address the main outcomes regarding CO₂ emissions and seaborne transport
384 costs, but, first an analysis of the proposed approach's suitability is necessary.

385 *3.1. Suitability of the proposed approach*

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

388 Table 10 presents a comparison of some global outcomes of the present approach to literature references. An
389 overestimation of 23% is shown regarding the total cargo quantity transported by sea. This excess is probably
390 transported by another transport modality. The total transport work found is closer to the value reported in the same
391 reference, being underestimated by only 5.5%. Regarding CO₂ emission, model 1 (M1) overestimates the reference
392 value by 12.1% whereas model 2 (M2) overestimates it by 8.8%. These emission inaccuracies can be taken as coherent
393 since the load was overestimated as well.

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

403 *3.1.1. The main outcome of CO₂ emissions*

404 The two models of technical efficiency developed here gave similar results in terms of global CO₂ emissions due
405 to international seaborne shipping, as can be see in Fig. 4. The reference case of model M1, based on the technical

406 efficiency reported in the EU THETIS MRV ship database, returns a result about 3% higher than model M2, based
 407 on the fuel consumption of main engines and auxiliary engines. The CO₂ emission for 2008 (IMO reference level) is
 408 shown as a red full line whereas IMO target (50% reduction) is shown as a red dotted line. Therefore, one can see that
 409 there was an increment of over 5% in GHG emissions from 2008 to 2017 (REF), contrary to the reduction objective.
 410 This highlights the need to implement measures to reach the target.

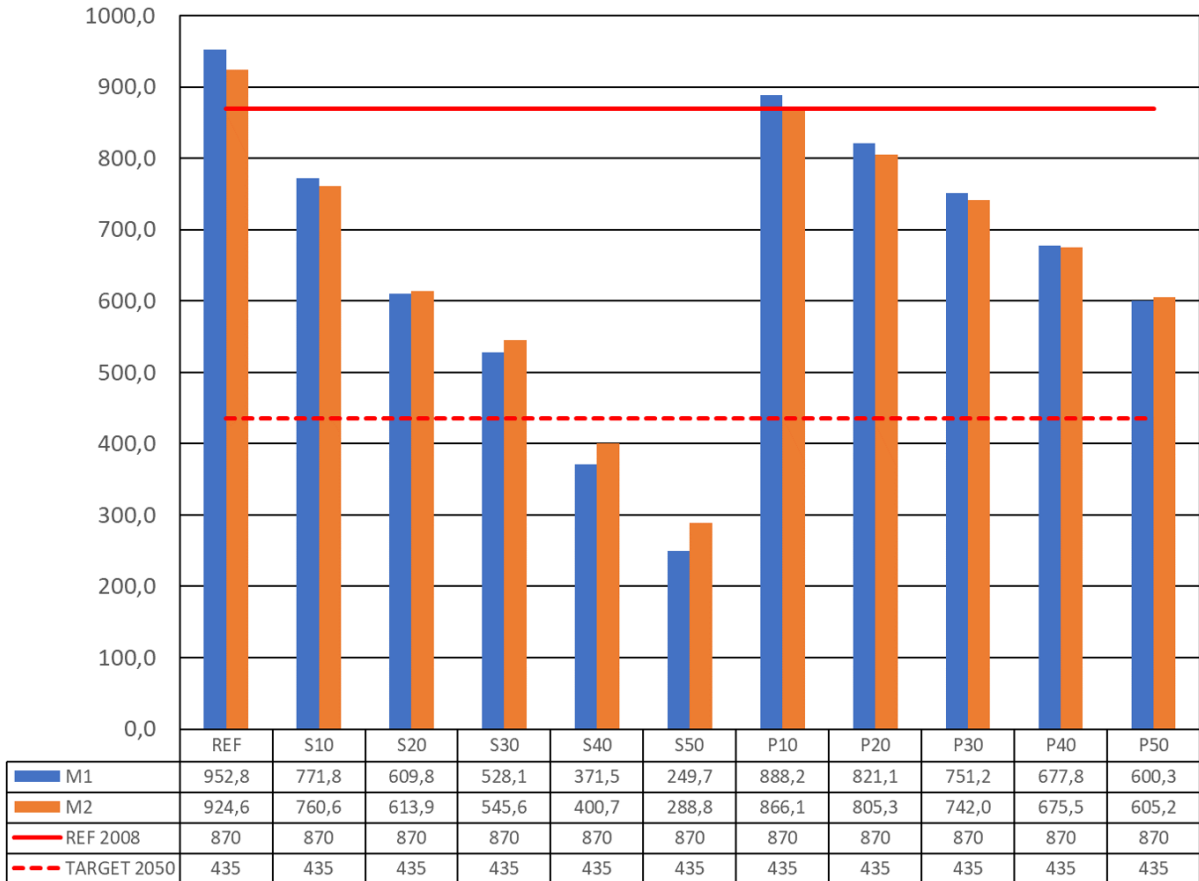


Figure 4: The environmental effect of slow steaming by models M1 and M2, reported in millions of tons of CO₂ for 2017.

411 Figure 5 shows that the higher the reduction in speed or power is, the lower the emissions generated are, and
 412 that percentage reductions of speed are significantly more effective than on power. A 50% speed reduction renders
 413 a 68% CO₂ emission reduction whereas the same power reduction renders a 34% emission reduction, compared to
 414 2017 (REF). Hence, a prescriptive and uniform reduction of the worldwide ship fleet speed of over 30% would be
 415 required to reach the IMO target. This corresponds to a propulsion power reduction of more than 50%. The higher
 416 CO₂ emission observed for S30 and S40 in model M2 is generated by the additional power consumed by the engine
 417 blowers.

418 By looking at the division of CO₂ emission by ship type in Fig. 6 it can be seen that the highest contribution

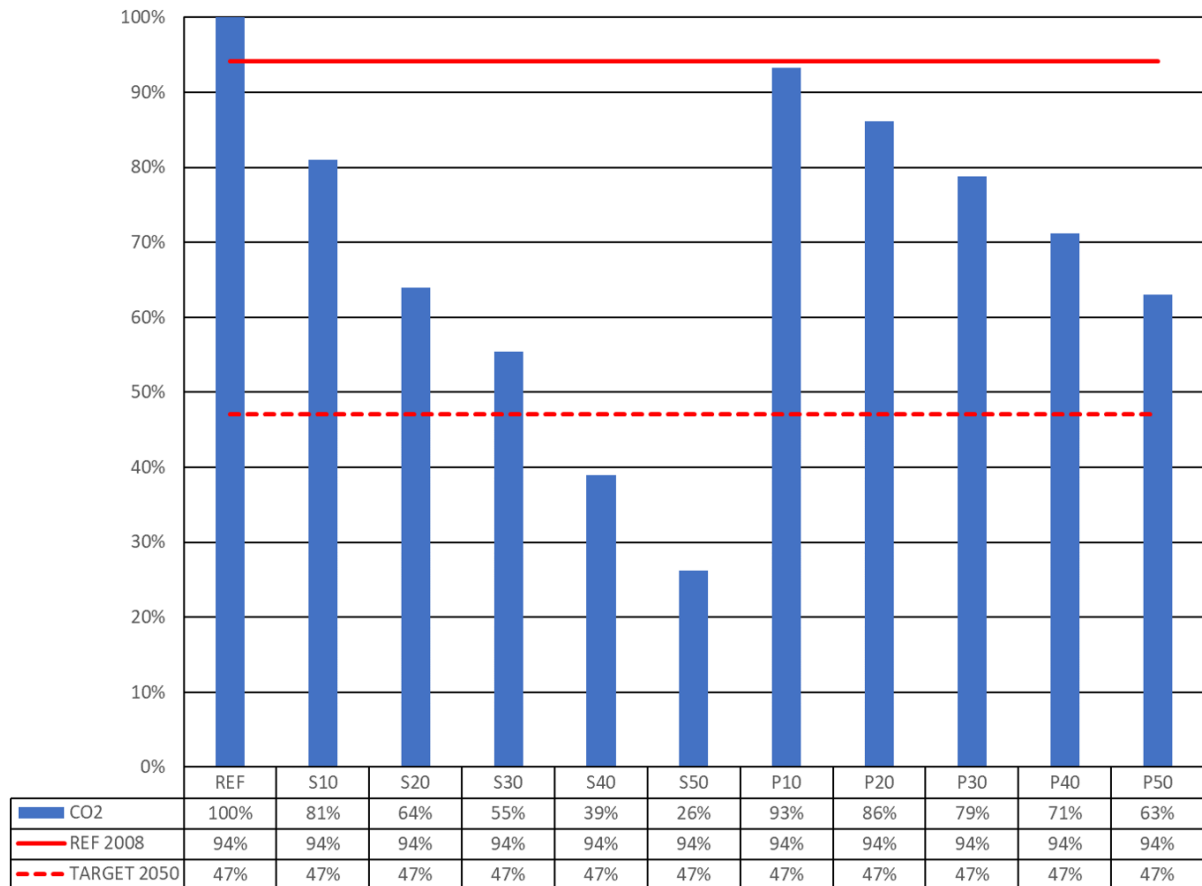


Figure 5: The environmental effect of slow steaming of model M2, reported in percentage of CO₂ emission for 2017.

419 comes from the oil tankers, followed by bulk carriers and then container carriers. Since each ship type is subject to
 420 a uniform percentage speed reduction, the contributions of the three main ship types become closer as the reduction
 421 increases. Therefore, with a speed reduction of 50% (S50), the contributions of oil tankers, bulk carriers and container
 422 carriers become almost the same. Given this scenario, in which those three ship types are together responsible for over
 423 93% emissions, an alternative would be to adopt higher speed or power reductions only for the larger contributors.

424 Figure 7 shows the effect of the slow steaming strategy on the annual global CO₂ shipping emissions per macro-region.
 425 The main contributor is Europe (EU), followed by Asia (AS) and North America (NA). Europe represents almost 34%
 426 of the worldwide CO₂ emissions whereas those three larger contributors represent together over 77%. Brazil (BR)
 427 accounts for around 6% of the global shipping emissions whereas the rest of South America (SA) accounts for around
 428 3%.

429 3.2. Annual global seaborne export transport costs

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

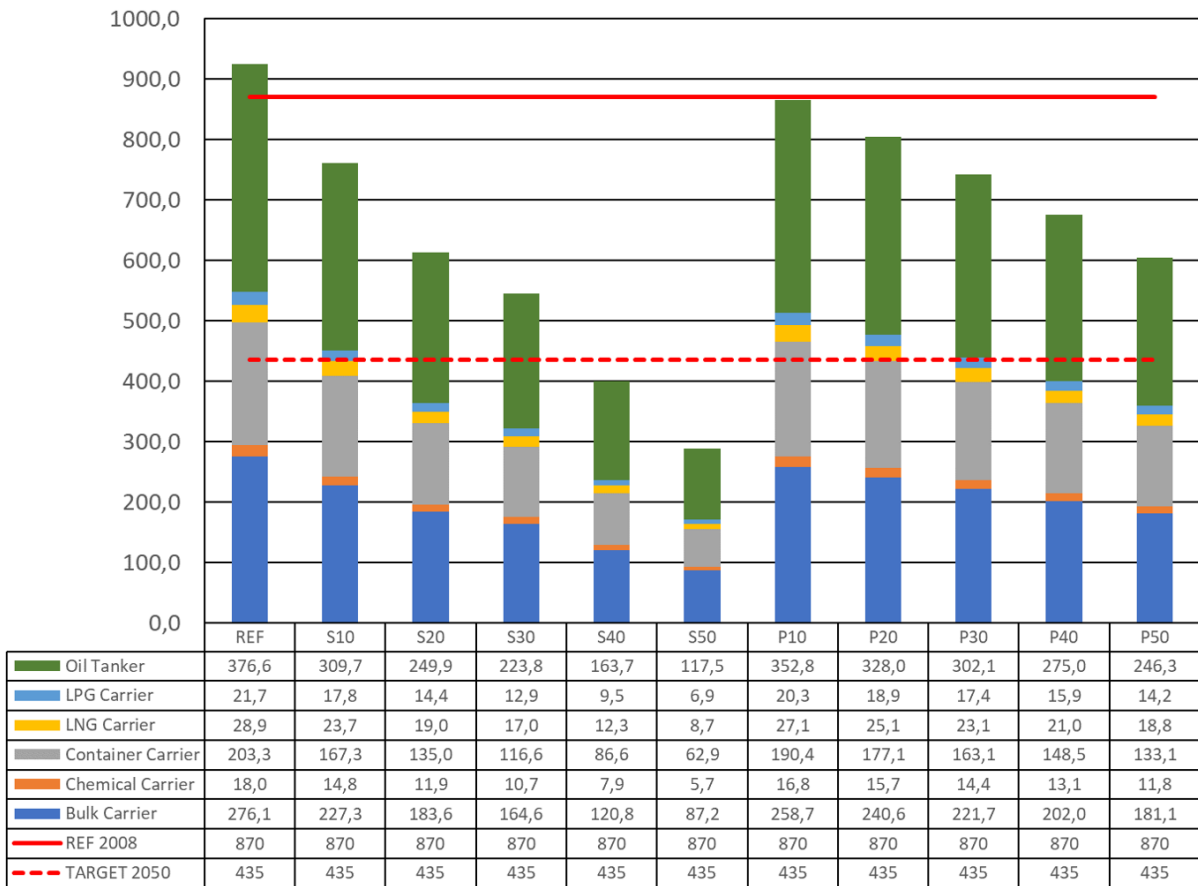


Figure 6: The environmental effect of slow steaming by ship type, reported in millions of tons of CO₂ for 2017.

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

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

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

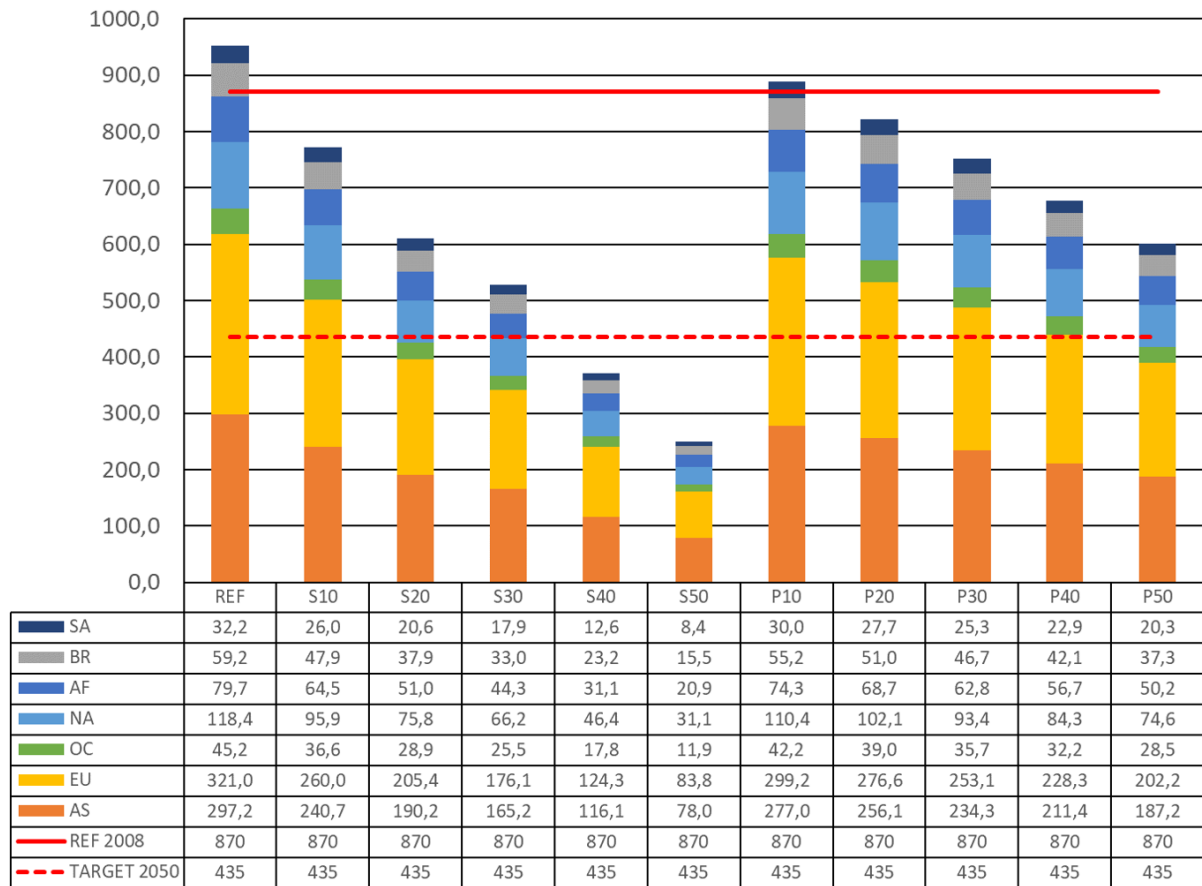


Figure 7: The environmental effect of slow steaming by macro-region, reported in millions of tons of CO₂ for 2017.

445 The main contributor is Asia (AS), followed by Europe (EU) and then Oceania (OC). Notice that AS and EU changed
 446 positions and OC is a larger contributor than North America (NA) when comparing the economic scenario with
 447 the environmental scenario (Fig. 7). While a 10% speed reduction (S10) is economically beneficial for every
 448 macro-region, a 20% reduction (S20) is no longer beneficial for NA, Africa (AF) and EU. The only macro-region
 449 that always benefits from speed reductions until 40% (S40) is OC. Like for ship types (Fig. 9), the speed reduction of
 450 50% (S50) would cause higher costs for every macro-region when compared with 40% (S40).

451 4. Conclusion

452 This work provides a quantitative assessment of cost and environmental aspects affected by the implementation of
 453 a slow steaming strategy for the world merchant fleet. The cost aspect was assessed by the total annual cost composed
 454 of capital expenditures (CAPEX), operating expenditures (OPEX) and voyage expenditures (VOYEX). In turn, the
 455 environmental aspect was assessed by annual CO₂ emissions. The world seaborne trade (exports) was used to simulate
 456 the world maritime transport network and investigate various scenarios of speed and power reductions.

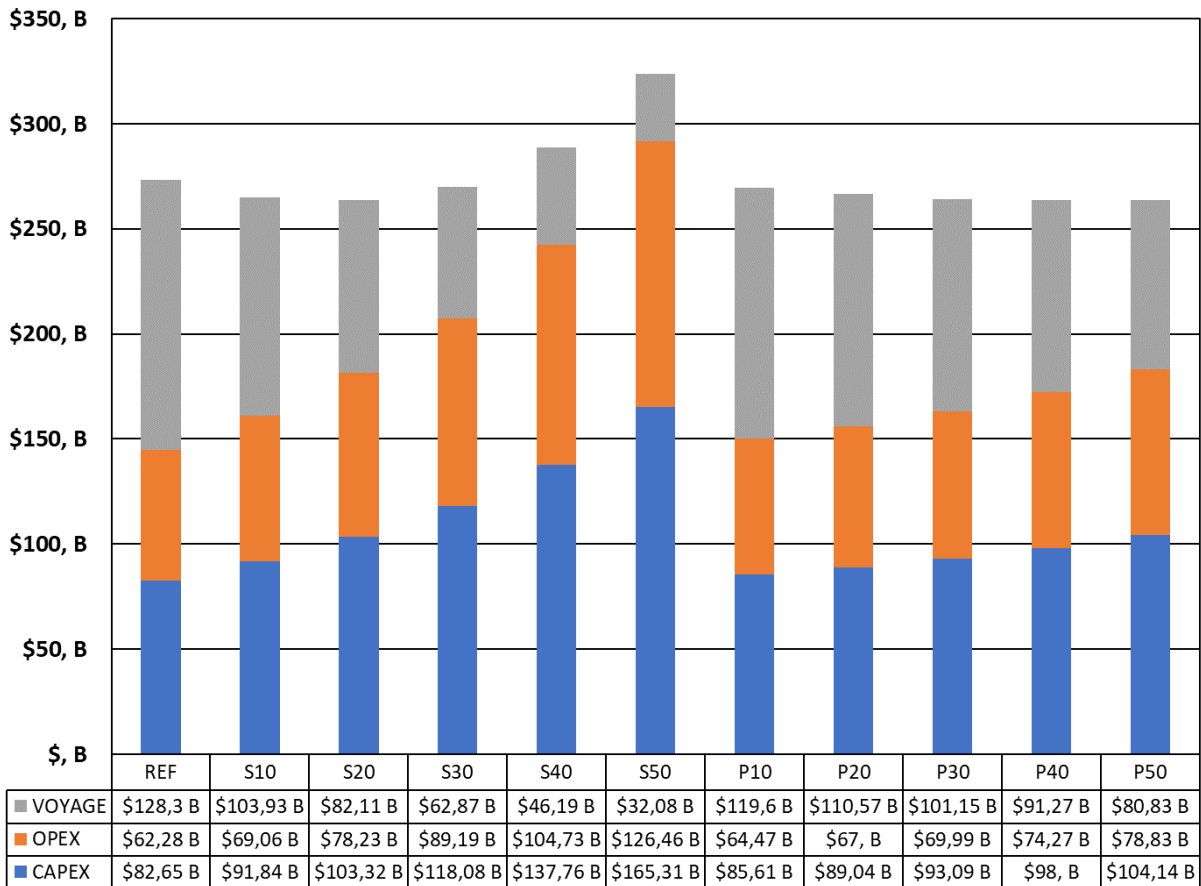


Figure 8: The economic effect of slow steaming by cost category reported in billions of USD for 2017.

457 By examining the environmental results, one can see that higher reductions of speed or power are associated
 458 with lower emissions generated, and that speed reduction is significantly more effective than power reduction. A
 459 uniform reduction of the fleet speed of just over 30% would be required to attain the IMO's target. Since over 93% of
 460 CO₂ emissions come from only three ship types and three macro-regions are responsible for over 77% of emissions,
 461 implementing different reductions per ship type or macro-region would be reasonable alternatives.

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

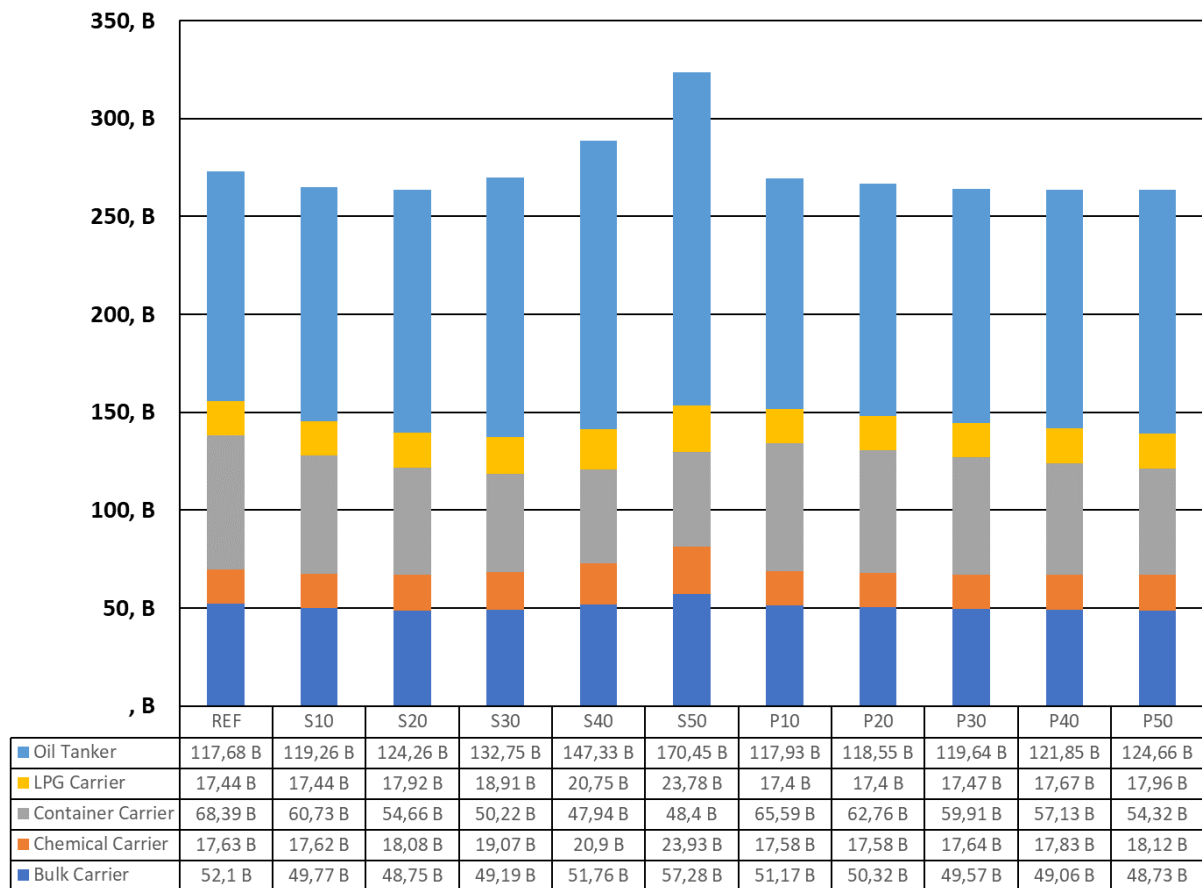


Figure 9: The economic effect of slow steaming by ship type reported in billions of USD for 2017.

470 Summarizing, a speed reduction of just over 30% would be enough to reach the target of 50% drop in CO₂
 471 emissions in 2050 versus 2008. However, this was found without considering any time-dependent variation in global
 472 seaborne trade. Depending on the growth in seaborne trade in future years, the necessary speed reduction could
 473 be significantly different from this value. Since container carriers were found to benefit economically from speed
 474 reductions until 40%, this ship type could be prioritized for higher speed reductions. Furthermore, container carriers
 475 are in third position among those most responsible for CO₂ emissions.

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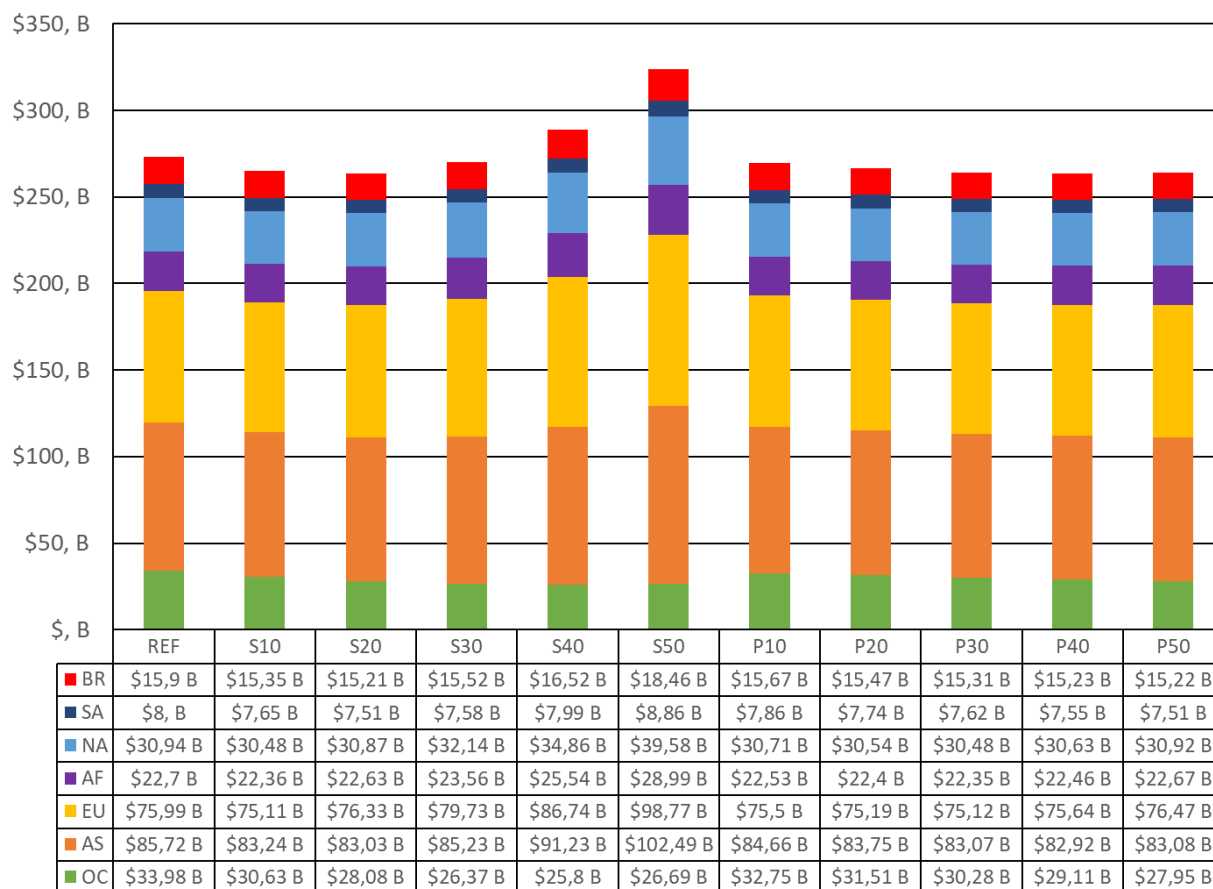


Figure 10: The economic effect of slow steaming by macro-region reported in billions of USD for 2017.

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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)	<i>LF</i>
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%	
S20	-20.00%	
S30	-30.00%	Service speed
S40	-40.00%	
S50	-50.00%	
P10	-10.00%	
P20	-20.00%	
P30	-30.00%	Propulsion power
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
Bulk Carrier	10000 - 19999	DWT	Container Carrier	100 - 999	TEU	LPG Carrier	up to 999	m ³
	20000 - 24999			1000 - 1999			1000-1999	
	25000 - 29999			2000 - 2999			2000-4999	
	30000 - 39999			3000 - 3999			5000-9999	
	40000 - 49999			4000 - 4999			10000-19999	
	50000 - 64999			5000 - 5999			20000-44999	
	65000 - 79999			6000 - 6999			45000-64999	
	80000 - 99999			7000 - 7999			65000 and larger	
	100000 - 119999			8000 - 8999			up to 4999	
	120000 - 159999			9000 - 9999			5000-19999	
160000 and larger	10000 - 11999	20000-39999						
Oil Tanker	10000 - 24999	DWT	Container Carrier	12000 - 13999	TEU	LNG Carrier	40000-59999	m ³
	25000 - 39999			14000 - 14999			60000-99999	
	40000 - 54999			15000 - 17999			100000-119999	
	55000 - 84999			18000 and larger			120000-129999	
	85000 - 124999						130000-139999	
	125000 - 159999						140000 and larger	
	160000 - 199999							
	200000 - 319999							
320000 and larger								
Chemical Carrier	up to 10000	DWT						
	10000 - 19999							
	20000 - 29999							
	30000 - 39999							
	40000 and larger							

Table 7: Non-dimensional conversion factor (C_F) between fuel consumption and CO₂ emission.

Machinery	Fuel type	C_F [kgCO 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 M2 - 924.8	+12.1 +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 28.0	57.0	Bulk carrier	53.0	53.0	-7.0
			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	