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System Dynamics Modelling Of Maritime GHG Emission Measures Impact Assessment

By

Istanbul Technical University, Maritime Faculty

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(GEMIMA-MOD)

Theme: 3

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Abstract

Greenhouse gas (GHG) emissions derived from ships have increased continually until 2018. International Maritime Organization (IMO) starts to adopt initiatives for reducing GHG emissions from ships since 2018. Now, by 2030 and 2020, IMO presented technical and operational steps, such as alternative fuels, propulsion and power system, hull and structure, voyage optimization, and energy management in the road map created to develop a comprehensive new strategic plan for achieving such as net zero emissions. However, stakeholders need to understand the long-term consequences of carbon reduction measures of IMO by simulating the dynamic interactions among many elements that affect emissions. In this context, modelling the dynamics that impact the system will be valuable in mitigating future GHG emissions and attaining net zero emission goals. This work aims to build a systematic strategy for developing a model that utilizes system dynamics to evaluate the possible long-term impacts of carbon reduction initiatives and laws on ships, as well as to forecast future CO2 emissions. This study specifically examines the global emissions generated by maritime vessels. The framework merely offers the dynamics and their accompanying mathematical equations as described in the existing literature. In this study, techniques for reducing GHG emissions are offered to gain a better understanding of how to treat emissions. The forthcoming study will integrate data on dynamics and IMO initiatives into the System Dynamics (SD) model to deduce strategic outcomes for reducing GHG emissions. The model offers a base for comprehensive framework for analysing the dynamics of GHG emissions in maritime sector. It also allows for forecasting future trends, evaluating policy options, and engaging stakeholders by simulating the dynamic interactions including as fuel usage, vessel features, regulatory frameworks, and technological improvements. This empowers decision-makers to navigate the complexities of sustainability and steer the shipping industry towards a greener and more resilient future.

Key words: *ship GHG, greenhouse gas emission, CO2 emissions in maritime, system dynamic model*

1. Introduction

Maritime transport is at the forefront of the climate change challenge. A strategic industry handling over 80% of world merchandise trade by volume and more than 70% of its value being maritime transport, shipping and ports face the dual challenge of cutting their carbon footprint and building their resilience to withstand unavoidable climate change impacts better. Both climate change mitigation and resilience building are crucial to future-proofing the maritime transport sector [1].

According to the statistics of the International Maritime Organization (IMO), while green house gas (GHG) emissions in total worldwide transportation were 977 million tons in 2012, this rate reached 1,076 million tons in 2018. With this increase of 9.6%, the global emission share of shipping has increased from 2.76% to 2.89% in 2018 [2]. IMO, being the United Nations body with the authority to govern the shipping industry, has established several methods and rules with the objective of mitigating GHG emissions originating from ships. At this point, in 2018, IMO adopted an initial strategy on the reduction of GHG emissions from ships, setting out a vision which confirms IMO's commitment to reducing GHG emissions from international shipping and to phasing them out as soon as possible. More specifically, under the identified "levels of ambition," the initial strategy envisages for the first time a reduction in total GHG emissions from international shipping which, it says, should peak as soon as possible and to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008, while, at the same time, pursuing efforts towards phasing them out entirely [3].

IMO demonstrates its commitment to achieving GHG reduction initiatives and targets by strategically collaborating with the International Association of Ports and Harbors (IAPH) to reduce GHG emissions from shipping companies and ports [2]. IMO ensures the integration of these strategic collaborations into the maritime sector in line with agreements that are effective on a global scale. With the Paris Agreement signed in December 2015, it was decided by many governments to halve GHG emissions by 2030 and reduce carbon neutrality to net zero around 2050, in line with the targets of reducing GHG emissions [4]. Many organizations and partnerships are being framed towards 2050 net zero GHG targets.

At this point, the significance of this project is that modeling based on the dynamics affecting the system will be useful in reducing future GHG emissions and achieving net zero emission targets. For this purpose, in this study, it is aimed to establish a systematic approach for developing a model that uses system dynamics to evaluate the potential long-term effects of carbon reduction initiatives and regulations on ships, as well as to predict future CO2 emissions. This study focuses on the worldwide emissions produced by ships. The framework just presents the dynamics and their corresponding mathematical equations from the literature. Additionally, in this study, IMO strategies for GHG emissions are presented to understand the dynamics for emission treatment. Furthermore, this project will incorporate data on dynamics and IMO initiatives into the SD model to derive strategic outcomes for lowering GHG emissions.

1.1 Research Objectives

The research objectives are as below:

i. to obtain a reliable and validate model by using agent-based system dynamics (SD) for maritime transportation system to understand the impact of GHG measures.

ii. to introduce the interaction and relation of components of maritime transportation system such market, users, stakeholders, states, and fleets.

iii. to study the importance and essence of GHG emissions in maritime as part of a holistic approach throughout a ship's life cycle

iv. to examine the key dynamics for GHG emissions in maritime and the potential impacts of them on GHG emissions

v. to investigate the nature of the system dynamics modelling for GHG emissions along with the significant impacts they can introduce to the Maritime environment in case of various scenarios.

vi. to explore the different scenarios for GHG emissions and identify their motives in order to forecast measures of GHG emissions for future in maritime and recognize the effects on the IMO's initial strategies.

vii. to identify the main aspects that contribute to the mitigation of the GHG emissions in maritime and propose a framework and modelling for addressing the exposures.

viii. to introduce a "Market Agent Based System Dynamics Modelling for Maritime Climate Actions" with state-of-the-art model that can be used by IAMU and can be enhanced throughout years.

2. Methodology

This project will be consisted of six stages. The progress of project and all the management items will monitor continuously to assess the status of project implementation in relation to the approved work packages and budget. The working packages are listed below.

Work Package 1: Performing Literature Review and Defining Dynamics affecting GHG Emissions

Work Package 2: Data Collection

Work Package 3: Design of System Dynamics Modelling for GHG Emissions

Work Package 4: Test and Verification of the System Dynamics Model

Work Package 5: Development and Implementation of Scenarios for the System Dynamics Model

Work Package 6: Development Strategies and Policies about GHG Emissions

WP1: Performing Literature Review and Defining Dynamics affecting GHG Emissions

T1.1: Academic and technical literature that is on the GHG emissions and climate action in maritime, international regulations on GHG such as IMO, DNV-GL or other maritime organizations' publications, international conventions, technical papers, and national regulations on GHG will be searched.

T1.2: Comprehensive and complex dynamic composites affecting GHG in maritime will be determined according to findings in T1.1 in the scope of IMO's initial strategy and by taking expert opinion in this field.

WP2: Data Collection

T2.1: Data for dynamics determined in WP1 will be collected from manufacturers' brochures, technical papers, related reports, and regulations for providing historical information to system dynamics model.

WP3: Design of System Dynamics Modelling for GHG Emissions

T3.1: Cause and effect relationship between dynamics and the type of variables in the system dynamics modelling will be build and accordingly mathematical relationship and equations will be defined for all dynamics.

WP4: Test and Verification of the System Dynamics Model

T4.1: The collected data in WP2 will be used for test and verification of the developed system dynamics modelling of GHG for maritime with two case studies. The case studies can be obtained from maritime accidents reports on GHG. The data for dynamics in the developed model is obtained from reports and the analysis results of developed model are compared with the results stated in the reports. In this way, the test and verification of the system dynamics model for GHG emissions is performed.

WP5: Development and Implementation of Scenarios for the System Dynamics Model

T5.1: After proofing the reliability and validity of the developed model in WP4, new possible scenarios will be developed according to future improvements and suggestions for GHG emissions such as using of the cases about renewable energies.

T5.2: New scenarios will be developed via following IMO circular, searching academic paper, technical paper and reports, and making brainstorms between project partners.

WP6: Development Strategies and Policies about GHG Emissions

T6.1: According to analysis results for scenarios implemented in WP5, effective and fundamental strategies and policies for GHG emissions in maritime will be presented in the scope of the IMO's strategies.

3. System Dynamics Modelling (SD Modelling)

3.1 Model Settings

Many various areas, including business, engineering, physics, military science, agriculture, and weather forecasting have all come to stress systems thinking as an organizing paradigm in the last few years. Despite the fact that systems thinking is not a single subject, there are several essential systems-thinking ideas and methodologies that are similar across fields: (i) An emphasis on a network-centric approach that encourages relationships between individuals and organizations across traditional disciplines and fields in order to achieve relevant goals and objectives; (ii) the development of models and projections, using a variety of analytic approaches (e.g., differential equations, agent-based modelling, system syst.) [5].

Using system dynamics (SD) as a methodology and computer simulation modelling approach, complex topics and problems may be framed, understood, and discussed. And it is extensively utilized to acquire insight into a complex, dynamic, and non-linearly interacting system. Because of this, a system may be shown as a continuous feedback loop [6].

System dynamics is a modelling approach that uses analytic reasoning. Forrester's pioneering work on "industrial dynamics" in the 1958s is credited with its inception. Dynamic financial analysis relies heavily on models. Industrial activity may be described in a "systematic fashion" using these models. In other words, it teaches us how the system's behaviour is derived from the interactions among its pieces." To better comprehend complex systems, the system dynamic model incorporates both qualitative and quantitative features and tries to acquire insights into system behaviour. Using "causal maps" or "influence diagrams," the qualitative aspect involves examining the structure of a system and the interrelationships between its components. Quantitative analysis requires creating a computer model that simulates the movement of materials and information throughout the system. Jay Forrester established the modelling approach system dynamics (SD) in the 1950s to address social, economic, and technological issues [7]. Based on the concept that feedback processes are ubiquitous in human interactions, a socio-economic or socio-technical system may be treated as a feedback structure, whose complex behaviour is formed by the interaction of multiple (potentially non-linear) loops over time. This technique is based on. To better understand the dynamic complexity of systems, SD models may be used to learn about the current system's best policies as well as to enhance the system's behaviour via parameter or structural modifications. System dynamics modelling principles may be found in a wide range of publications [8-11].

It is important to figure out the system's internal structure, as well as how various components interact with one another, and then it is fun to play around with different relationships inside the system by simulating different possibilities. Structure and behavior are linked in SD via the idea of information feedback and control [12]. Five iterative phases may be described in the system dynamic method as seen in Fig. 1 [13].

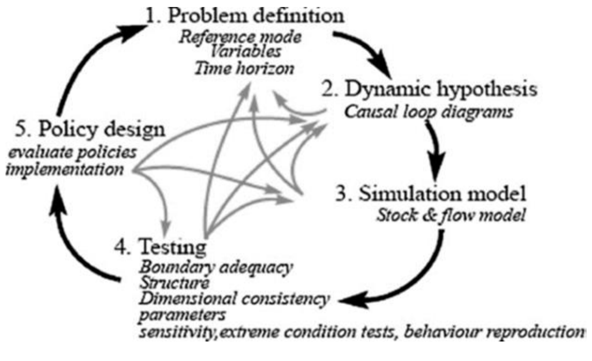


Fig.1. System dynamics model process [13]

1. Problems with dynamic systems begin with a clear research goal. Determined by the issue, the appropriate system limits of the problem may be found by determining which factors should be included and which should be removed. Identifying the problem's archetype and the relevant temporal horizon is essential.

2. A causal loop diagram is drawn, and stock and flow diagrams are used to show how the dynamic hypothesis is being tested.

3. The model is then implemented for simulation modelling as an iterative process.

4. Model structure and filter variables may be tested for feasibility and accuracy via testing. The structure is more important than the parameters in many feedback models. As a result, various model structures may be tested using the modelling's scalability. If you are looking to improve the accuracy of your parameters, parameter sensitivity tests may help.

5. Policy analysis and design may begin after a decent degree of trust in the model is established. It is possible to create an effective policy by simply comparing the outcomes of several situations, which are then automatically enumerated or shown graphically in software.

Sterman [14] stated the complex functions of system dynamics as follows:

- Constantly change: All dynamics is change. What may seem to be constant is actually observed to fluctuate over an extended period of time. Systems undergo changes at several temporal scales, and these distinct scales occasionally interact with each other. For instance, Bullmarkets can go on for years, then crash in a matter of hours.
- Tightly Coupled: The players inside the system engage in robust interactions with each other and with the environment. All things are interconnected. It is impossible to do only a single task.
- Controlled by Feedback: Due to the strong interconnections between individuals, our activities have a reciprocal effect on themselves. The choices we make have the power to modify the condition of the world, leading to transformations in the environment and prompting others to take action. As a result, a new scenario emerges, which in turn impacts our subsequent actions. This feedback gives rise to dynamics.
- Nonlinearity: Nonlinear systems exhibit a lack of proportionality between cause and effect. Additionally, the behaviour observed in one part of the system, close to the current operating point, may not be applicable to other areas or states of the system. Nonlinearity frequently emerges as a result of the fundamental principles of physics governing system
- History-Dependent: Choosing a particular road often excludes the possibility of choosing alternative routes and ultimately defines the final destination (path dependency). Several activities are irreversible. Stocks and flows, along with extended time delays, often result in distinct time constants for actions and reversals.

3.2 Causal Loop

It can be said that system dynamics is a technique for analysing and controlling complicated feedback systems, such as those found in social decision-making systems. A wide variety of feedback systems have benefited from its use. There have been many uses of the World system, but feedback is the distinguishing feature. When X affects Y and Y, in turn, affects X, we say that there has been a feedback effect.

There are two sorts of casual loops: causal loops and causal maps. Casual loops are feedback loops, while causal maps are causal maps that illustrate the behaviour of the chosen variable and all its related variables. When two variables are linked by a functional dependency, correlation regression assumes that the first variable's magnitude is determined by the second variable's magnitude. An example of causal loop is given in Fig. 2 [13].

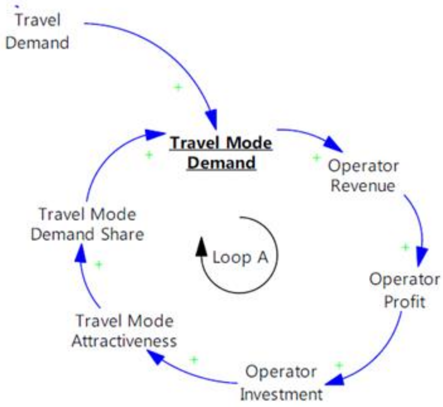


Fig. 2. An example of causal loop [13]

3.3 SD Model

Steerman [15] stated that two important concept of system dynamic tool is stock and flow with its feedback loop. Stocks are accumulation of systems and point out the current situation of the system while flows are used for defining the change in stock by time goes. In Fig. 3, example of stock flow is given.

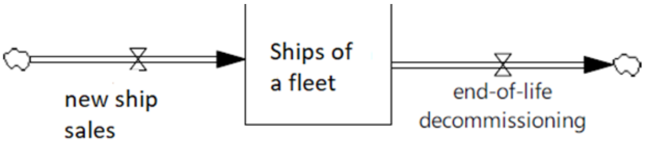


Fig. 3. An example of stock and flow [15]

Based on these procedures and processes, system Dynamics tool can be used to understand the behaviour of the system components and their relationship between each other by time scales. This discipline deals with dynamic policy problems of systemic, feedback nature. The purpose of a system dynamics study is to understand the causes of a dynamic problem, and then search for policies that alleviate/eliminate them. This specific purpose necessitates the adoption of a particular philosophy of modelling, analysis, and design. The structure of a system dynamics model consists of the set of relations between model variables, mathematically represented in the form of equations. That is, the structure of a system dynamics model is a set of differentials and/or difference equations. The fundamental of system dynamics model is consisted of a system of differential equations which are numerically solved in a sequence of time steps [16].

The analytical (mathematical) solution of a dynamic model, if obtainable, would give the exact formula for the dynamic behaviours of variables. So, one way of obtaining the dynamic behaviour of a model is solving it analytically. This is often possible in linear cases, but very rarely possible in non-linear ones. In such cases, the dynamic behaviour of the model is obtained by simulation. Simulation is essentially a step-by-step operation of the model structure over compressed time. Much like the operation of the real structure over real time, the model structure operates over simulated time, so that the dynamics of model variables gradually unfold [17]. Short term, midterm and long-term effects can be simulated effectively through the system dynamic models. An example of system dynamics model design for vehicles has been given in Fig. 4.

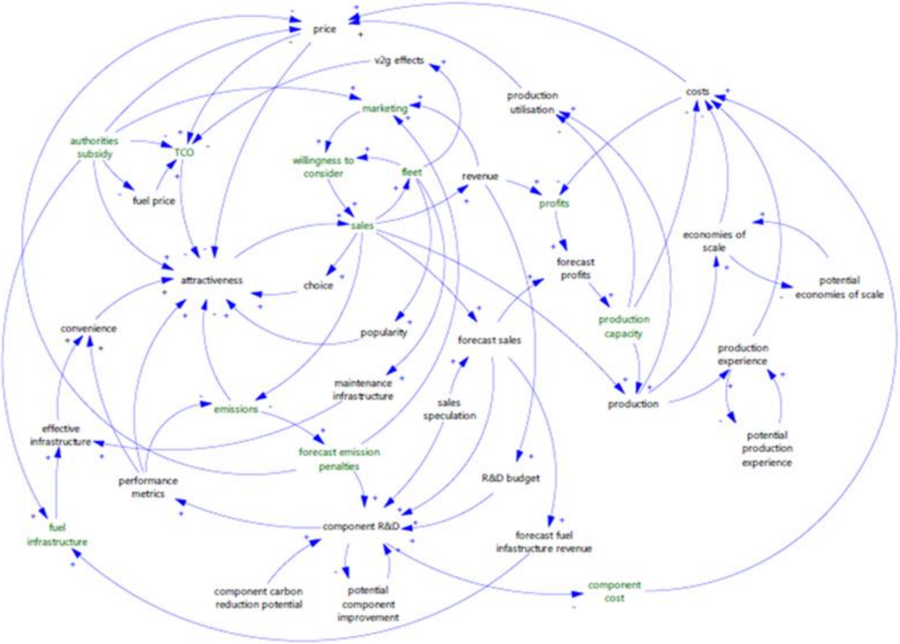


Fig. 4. An example of overall causal loop diagram for a market agent-based systems dynamics tool [17]

3.4 Comparing SD Model with Other Modelling Approaches

In addition to System Dynamics Modeling, several other modeling approaches can be used to assess the efficacy of maritime GHG reduction strategies. Each approach has its strengths and weaknesses, depending on the specific aspects of GHG reduction being studied. Table 1 shows the alternative models and a comparison of them with System Dynamics Modeling. However, SD is the best model to assess the GHG reduction strategies in terms of exceling in capturing dynamic, time-dependent behavior, feedback loops, and system-wide interactions, making it ideal for understanding complex system behaviour, long-term impacts and policy scenarios.

Table 1. Comparison of model approaches

Model Approaches	Description	Strengths	Weaknesses	Comparison with SD Model
Agent-Based Modeling (ABM)	ABM simulates the actions and interactions of autonomous agents (e.g., ships, ports, regulatory bodies) to assess their collective impact on the system. Each agent follows specific rules and can adapt its behavior based on changes in the environment or policies.	• Captures individual behaviors and heterogeneity among agents. • Flexible in modeling complex interactions and adaptive behaviors. • Useful for understanding the impact of micro-level decisions on the macro-level system.	• Can be computationally intensive, especially with a large number of agents. • Requires detailed data on individual agent behavior.	ABM offers a more detailed and granular approach, focusing on individual agents, while SDM focuses on aggregate system behavior.
Input-Output (I-O) Analysis	I-O analysis examines the relationships between different sectors of the economy and how changes in one sector (e.g., maritime transportation) affect others. It can be used to assess the environmental impact of economic activities, including GHG emissions.	• Provides a clear picture of inter-industry dependencies. • Can quantify the direct and indirect effects of maritime GHG reduction strategies on other sectors. • Useful for economic and environmental impact assessment.	• Assumes linear relationships between sectors. • Limited in handling dynamic and feedback effects.	• I-O analysis is more focused on economic interdependencies and less on dynamic feedback mechanisms, which are central to SDM. • SDM is more suitable for understanding time-dependent changes, while I-O analysis is more static.
Life Cycle Assessment (LCA)	LCA evaluates the environmental impacts of a product or service throughout its entire life cycle, from raw material extraction to disposal. For maritime GHG reduction, it can assess the lifecycle emissions of different strategies.	• Comprehensive assessment of environmental impacts across the entire lifecycle. • Identifies hotspots where GHG emissions can be most effectively reduced. • Standardized methodology widely recognized in environmental assessments.	• Data-intensive and time-consuming to conduct. • May not fully capture dynamic system interactions or feedback loops.	LCA is more product or process-specific, while SDM is system-focused.
Computable General Equilibrium (CGE) Models	CGE models represent the economy as a whole and simulate how economic equilibrium is affected by policy changes, including GHG reduction strategies. They consider market interactions, supply and demand, and economic feedback loops.	• Captures economy-wide impacts of GHG reduction policies. • Can model interactions between different sectors and regions. • Useful for policy analysis and economic forecasting.	• Complex and data-intensive. • Assumes markets always clear, which may not reflect real-world conditions.	• CGE models are more focused on economic equilibrium and market interactions, while SDM is better suited for understanding the dynamic behavior of systems over time. • SDM is generally more flexible in modeling non-linear feedback loops compared to CGE models.
Optimization Models	Optimization models are used to find the best solution (e.g., minimum GHG emissions) under given constraints. These models can include linear programming, mixed-integer programming, or evolutionary algorithms.	• Provides precise solutions for minimizing or maximizing objectives (e.g., GHG emissions). • Can handle multiple constraints and objectives simultaneously. • Useful for designing optimal GHG reduction strategies.	• May oversimplify complex systems by focusing on optimization rather than system dynamics. • Requires precise definition of objectives and constraints.	• Optimization models focus on achieving specific objectives, while SDM focuses on understanding system behavior over time. • SDM is more flexible in capturing complex interactions and feedback loops, while optimization models are more rigid but precise in their outputs.

4. IMO Strategies for GHG Emissions

4.1 Candidate measures for IMO GHG strategies

In September 1997, the International Conference of Parties to the MARPOL Convention approved Resolution 8 addressing ship CO2 emissions via the Protocol of 1997 to update MARPOL Annex VI. This resolution asked the Marine Environment Protection Committee (MEPC) to explore CO2 reduction options in light of CO2's link with other atmospheric and marine pollutants [18]**.** IMO gave indications of the steps it will take to reduce GHG emissions from ships in its Dec. 5, 2003. It was initiated with the decision A.963 (23) and IMO asked the Marine Environment Protection Committee (MEPC) to make plans on GHG emission reduction [19]. MEPC held its 72nd session in 2018, focusing on this issue. Short, medium and long-term measures that can be taken and the effects of these measures on States were emphasized and ultimately IMO Strategic objectives were determined in Fig. 5 [23]. The scope of the targets of these strategies was determined as supporting measures on capacity building, technical collaborations, research and development [20].

Candidate measures set out in this 2023 IMO GHG Strategy should be consistent with the following timelines [21][22]:

1. short-term GHG reduction measures are the measures finalized and agreed by the Committee between 2018 and 2023;
2. the basket of mid-term GHG reduction measures should be finalized and agreed by the Committee by 2025. Dates of entry into force and when the measure(s) can effectively start to reduce GHG emissions could be defined for the basket or for each measure individually;
3. other candidate mid-term GHG reduction measures could be finalized and agreed by the Committee between 2023 and 2030. Dates of entry into force and when the measure can effectively start to reduce GHG emissions would be defined for each measure individually; and
4. possible long-term measures could be measures finalized and agreed by the Committee beyond 2030, to be developed as part of the 2028 review of the IMO GHG Strategy.

Candidate short-term measures

Measures can be categorized as those the effect of which is to directly reduce GHG emissions from ships and those which support action to reduce GHG emissions from ships. All the following candidate measures represent possible short-term further action of the Organization on matters related to the reduction of GHG emissions from ships:

1. further improvement of the existing energy efficiency framework with a focus on EEDI and SEEMP, taking into account the outcome of the review of EEDI regulations;
2. develop technical and operational energy efficiency measures for both new and existing ships, including consideration of indicators in line with the three-step approach that can be utilized to indicate and enhance the energy efficiency performance of shipping, e.g. Annual Efficiency Ratio (AER), Energy Efficiency per Service Hour (EESH), Individual Ship Performance Indicator (ISPI), Fuel Oil Reduction Strategy (FORS);
3. establishment of an Existing Fleet Improvement Programme;
4. consider and analyse the use of speed optimization and speed reduction as a measure, taking into account safety issues, distance travelled, distortion of the market or to trade and that such measure does not impact on shipping's capability to serve remote geographic areas;
5. consider and analyse measures to address emissions of methane and further enhance measures to address emissions of Volatile Organic Compounds;

6. encourage the development and update of national action plans to develop policies and strategies to address GHG emissions from international shipping in accordance with guidelines to be developed by the Organization, taking into account the need to avoid regional or unilateral measures;
7. continue and enhance technical cooperation and capacity-building activities under the ITCP;
8. consider and analyse measures to encourage port developments and activities globally to facilitate reduction of GHG emissions from shipping, including provision of ship and shore-side/on-shore power supply from renewable sources, infrastructure to support supply of alternative low carbon and zero-carbon fuels, and to further optimize the logistic chain and its planning, including ports;
9. initiate research and development activities addressing marine propulsion, alternative low-carbon and zero-carbon fuels, and innovative technologies to further enhance the energy efficiency of ships and establish an International Maritime Research Board to coordinate and oversee these R&D efforts;
10. incentives for first movers to develop and take up new technologies;
11. develop robust lifecycle GHG/carbon intensity guidelines for all types of fuels, in order to prepare for an implementation programme for effective uptake of alternative low-carbon and zero-carbon fuels;
12. actively promote the work of the Organization to the international community, in particular, to highlight that the Organization, since the 1990's, has developed and adopted technical and operational measures that have consistently provided a reduction of air emissions from ships, and that measures could support the Sustainable Development Goals, including SDG 13 on Climate Change; and
13. undertake additional GHG emission studies and consider other studies to inform policy decisions, including the updating of Marginal Abatement Cost Curves and alternative low-carbon and zero-carbon fuels.

Candidate mid-term measures

Measures can be categorized as those the effect of which is to directly reduce GHG emissions from ships and those which support action to reduce GHG emissions from ships. All the following candidate measures represent possible mid-term further action of the Organization on matters related to the reduction of GHG emissions from ships:

1. implementation programme for the effective uptake of alternative lowcarbon and zero-carbon fuels, including update of national actions plans to specifically consider such fuels;
2. operational energy efficiency measures for both new and existing ships including indicators in line with three-step approach that can be utilized to indicate and enhance the energy efficiency performance of ships;
3. new/innovative emission reduction mechanism(s), possibly including Market-based Measures (MBMs), to incentivize GHG emission reduction;
4. further continue and enhance technical cooperation and capacity-building activities such as under the ITCP; and
5. development of a feedback mechanism to enable lessons learned on implementation of measures to be collated and shared through a possible information exchange on best practice.

Candidate long-term measures

All the following candidate measures represent possible long-term further action of the Organization on matters related to the reduction of GHG emissions from ships:

1. pursue the development and provision of zero-carbon or fossil-free fuels to enable the shipping sector to assess and consider decarbonization in the second half of the century; and

2. encourage and facilitate the general adoption of other possible new/innovative emission reduction mechanism(s).

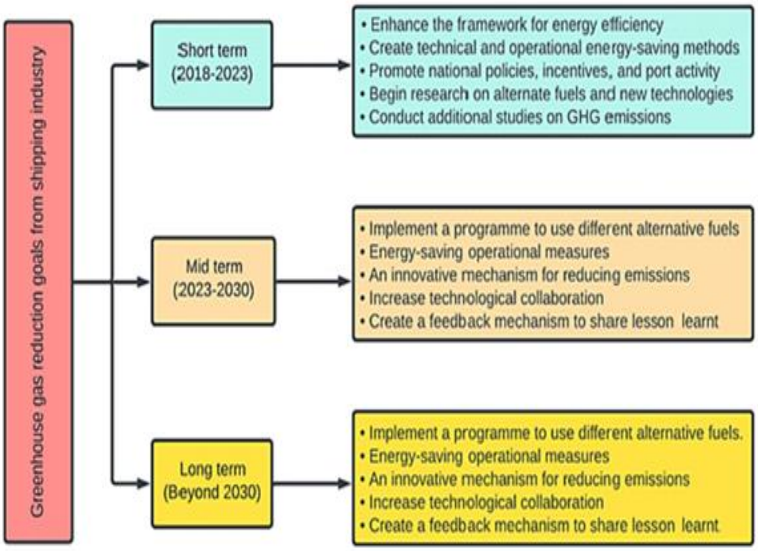


Fig. 5. Short-, medium-, and long-term steps of the initial strategy to reduce GHG emissions for maritime transportation [23]

4.2 Exist measures for GHG emissions

While creating the strategic plan for GHG reduction, a roadmap was used. Applications such as Ship Energy Efficiency Management Plan (SEEMP) and Energy Efficiency Design Index (EEDI) in 2013 are some of the technical and operational steps in the road map created to develop a comprehensive strategic plan. In October 2016, MEPC accepted the Data Collection System (DCS) at its 70th meeting and started voluntary data collection activities. In its 71st session in May 2017, topics such as current and future parameters and indicators, emission-reducing initiatives such as alternative fuels, cost, and benefit analyses and EEDI effects were discussed [24]. EEDI measures the energy efficiency of ships during the design phase. It encourages the use of more efficient designs and technologies to reduce CO2 emissions. SEEMP is a plan to improve the operational energy efficiency of ships. SEEMP promotes the adoption of fuel-saving operational practices.

Short-term decarbonization measures, adopted by way of revisions to chapter 4 of the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI [25], include the Energy Efficiency Design Index for Existing Ships (EEXI) and the Carbon Intensity Index (CII) rating scheme. These need to be implemented from 2023 onwards. These complement earlier rules, namely the EEDI focusing on newbuild ships only, and SEEMP [1]. The short-term measures are set to be reviewed by 2026 [26].

In 2018, IMO's GHG Strategies were adopted, and three targets were initially determined. Targets have been set to improve EEDI requirements for each ship type and phase, to reduce international shipping by reducing CO2 emissions by at least 40% in 2030 compared to 2008 and by at least 70% in 2050, and to reduce GHG emissions by at least 50% in 2050 compared to 2008. Within the framework of this strategic plan, speed reduction and speed optimization without affecting commercial activities, Annual Efficiency Ratio (AER), Fuel Oil Reduction Strategy (FORS), provision of ship and shore-side/on-shore power supply from renewable sources, infrastructure to support supply targets and improvements are aimed for issues such as of alternative low carbon and zero-carbon fuels, and to further optimize the logistic chain and its planning [3].

The EEXI is a technical measure in force since 1 November 2022 and applies to all existing ships of 400 gross tons (GT) or above. EEXI is a “sister” measure to EEDI and concerns design parameters of the vessels and measures their structural efficiency in terms of energy efficiency level per capacity mile [27].

To comply with EEXI standards, older vessels may need to undergo retrofitting, such as installing energy-efficient engines, optimizing hull forms, or incorporating energy-saving devices like Flettner rotors. These retrofits can significantly reduce fuel consumption and emissions, especially for older, less efficient ships. Ships that cannot economically meet the EEXI requirements may be phased out of operation, effectively reducing the global fleet's overall carbon footprint. This measure thus drives fleet renewal with more energy-efficient ships, contributing to GHG emission reductions. The EEXI is expected to have a substantial short-term impact on GHG emissions since it targets existing ships that may be operating with outdated technologies. Immediate reductions in emissions can be realized through compliance with the EEXI, particularly in the near term [70].

The CII is an operational measure that also applies to existing ships. Since 1 January 2023, ships of 5,000 GT and above must calculate their Attained CII, which links the CO2 emissions to the cargo carrying capacity over distance travelled, and rates the vessel on a scale of A to E. The CII is calculated according to the Annual Efficiency Ratio (AER), which is the ratio of CO2 produced in a year, divided by the product of dead weight tons multiplied by miles sailed in a year. CII ratings will be recorded in a ship’s SEEMP. If the ship is rated as D or E for three consecutive years, its SEEMP will need to be reviewed and include corrective actions to improve the rating. The annual carbon intensity reduction factor was equivalent to business-as-usual until entry into force; then 2 per cent from 2023 to 2026; and to be further strengthened for the period 2027 to 2030.

CII incentivizes shipowners and operators to adopt more fuel-efficient practices, such as optimizing voyage planning, reducing vessel speed (slow steaming), and improving hull and propeller maintenance. These operational improvements can lead to immediate reductions in fuel consumption and, consequently, GHG emissions. Vessels with poor carbon intensity performance may need to adopt energy-saving technologies, such as air lubrication systems, energy-efficient propellers, or waste heat recovery systems, to meet CII targets. These technological upgrades contribute to the overall reduction of GHG emissions from the maritime sector. By establishing a regulatory framework that tightens over time, the CII ensures a continuous push towards lower carbon emissions, aligning with the IMO's longer-term goals for decarbonization. This regulatory pressure may accelerate the adoption of alternative fuels, such as ammonia or hydrogen, in the medium to long term [71][72].

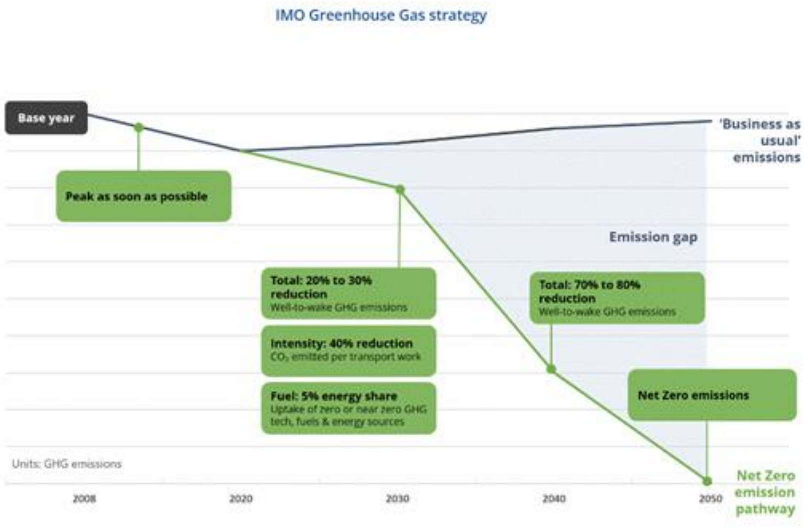
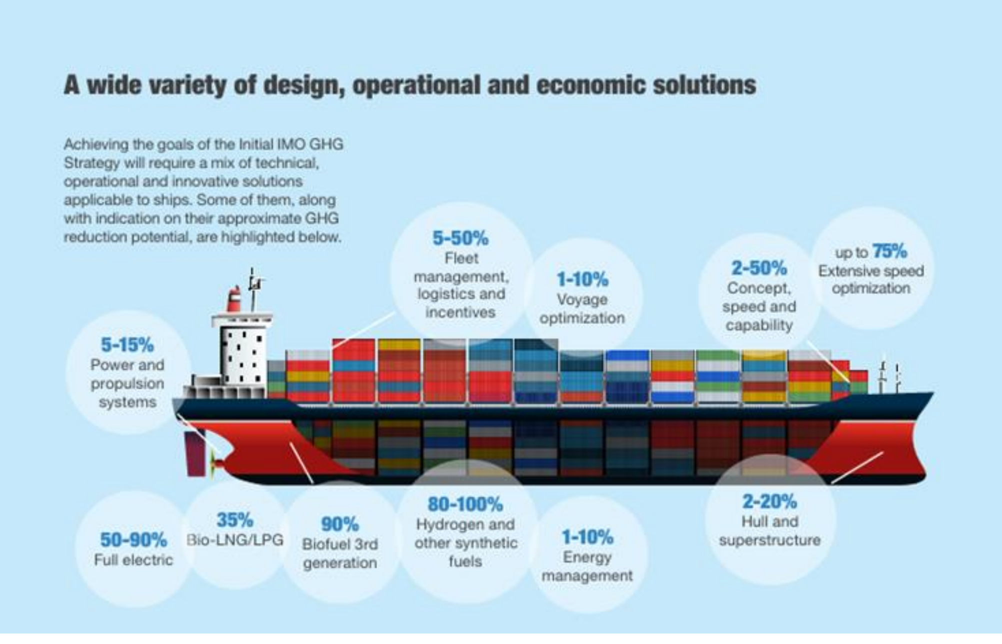


Fig. 6. IMO GHG strategy [28]

IMO will review the effectiveness of the implementation of the CII and EEXI requirements by 1 January 2026 at the latest and develop and adopt further amendments as required. Compliance should be ensured by both fag States and port States, which respectively issue and verify the existence of a statement of compliance in relation to fuel oil consumption reporting and operational carbon intensity rating, while the IMO provides implementation guidelines. A good CII score will require ships to operate efficiently by leveraging route optimization, fuel efficiency, and speed [25]. As the Carbon Intensity Reduction targets, IMO aims to reduce carbon intensity in international shipping by 40% by 2030 compared to 2008 levels. Additionally, the goal is to halve total GHG emissions by 2050 and achieve zero-emission shipping in the second half of the century. Fig. 6 also show the net zero emission pathway [28].

Alternative Fuels and Technologies are development and use of low-carbon or carbon-neutral fuels such as LNG, biofuels, hydrogen, and ammonia. Renewable energy sources like solar and wind power are also being implemented on ships. In terms of Carbon Pricing and Taxation, discussions and implementations of carbon pricing mechanisms and taxation policies continue to incentivize emission reductions. Furthermore, technological innovations in the maritime sector for the GHG emission reduction are wind-assisted propulsion systems, electric and hybrid propulsion systems, energy-saving devices. Wind-assisted propulsion systems technologies are like sails, rotor sails, and kite sails harness wind energy to reduce fuel consumption. Electric and hybrid propulsion systems as battery technologies and hybrid propulsion systems reduce fossil fuel consumption and emissions. Energy-saving devices as more efficient propellers, energy recovery systems, and low-friction coatings enhance the energy efficiency of ships.

For the next study, IMO solutions, which are in the category of design, operational, and economic, will be added into the SD model as the emission treatment dynamics [21][29][30]. Hence, the effect of these solutions on the GHG emissions can be shown as a holistic approach by the help of different scenarios. To accomplish the objectives of the Initial IMO GHG Strategy, a combination of technological, operational, and creative solutions that may be applied to ships will be necessary. There are many measures that a ship may undertake to enhance its rating, including hull cleaning to minimize drag, optimizing speed, installing energy-efficient light bulbs, and incorporating solar or wind auxiliary power for accommodation services. Highlighted on Fig. 7 are some of them, along with indications of their estimated greenhouse gas (GHG) reduction potential [31].


A wide variety of design, operational and economic solutions

Achieving the goals of the Initial IMO GHG Strategy will require a mix of technical, operational and innovative solutions applicable to ships. Some of them, along with indication on their approximate GHG reduction potential, are highlighted below.

Fig. 7. IMO solutions for GHG emissions [31]

Figure 8 displays the essential regulatory and implementation support measures included in the 2023 IMO Strategy on Reducing GHG Emissions from Ships. Market-Based Measures (MBMs) are a future regulatory approach under consideration by the IMO to further incentivize GHG reduction. In line with the work plan adopted at MEPC 55 (October 2006), potential Market-Based Measures (MBMs) have been considered in-depth since MEPC 56 (July 2006). MEPC 55 work plan ceased at MEPC 59 (July 2009), where the Committee recognized that technical and operational measures would not be sufficient to satisfactorily reduce the amount of greenhouse gas (GHG) emissions from international shipping in view of the growth projections of world trade. It was therefore agreed by overwhelming majority that an MBM was needed as part of a comprehensive package of measure for the effective regulation of GHG emissions from international shipping. In this regard, the Committee agreed upon a new work plan for the further consideration of MBMs culminating in July 2011 at MEPC 62. MBMs could include mechanisms such as carbon pricing, emissions trading schemes (ETS), or fuel levies, all of which place a financial cost on carbon emissions, encouraging the maritime industry to reduce its carbon footprint. By attaching a cost to carbon emissions, MBMs create a direct financial incentive for shipowners and operators to reduce their GHG emissions. This can accelerate the adoption of low-carbon technologies and alternative fuels, as well as the implementation of operational measures that reduce emissions. MBMs have the potential to drive significant global emissions reductions by making it more expensive to emit CO2. This economic pressure can lead to industry-wide changes, including shifts in fuel use, operational practices, and even changes in the global supply chain to reduce emissions. The introduction of MBMs can stimulate innovation in the maritime industry, as companies seek cost-effective ways to reduce their carbon liability. This could lead to the development of new technologies, fuels, and practices that contribute to long-term decarbonization. MBMs can help align the maritime sector with broader global climate goals, such as those outlined in the Paris Agreement. By incorporating carbon pricing or similar mechanisms, the maritime industry can contribute to global efforts to limit temperature rise by reducing GHG emissions [2] [73]. In the IMO 2023 revision strategy, targets have been set for medium-term GHG emission reduction, encouraging the energy transition in shipping and providing fair and equal conditions for the passage of all fleets by arranging economic mechanisms in the pricing of fuels [21].

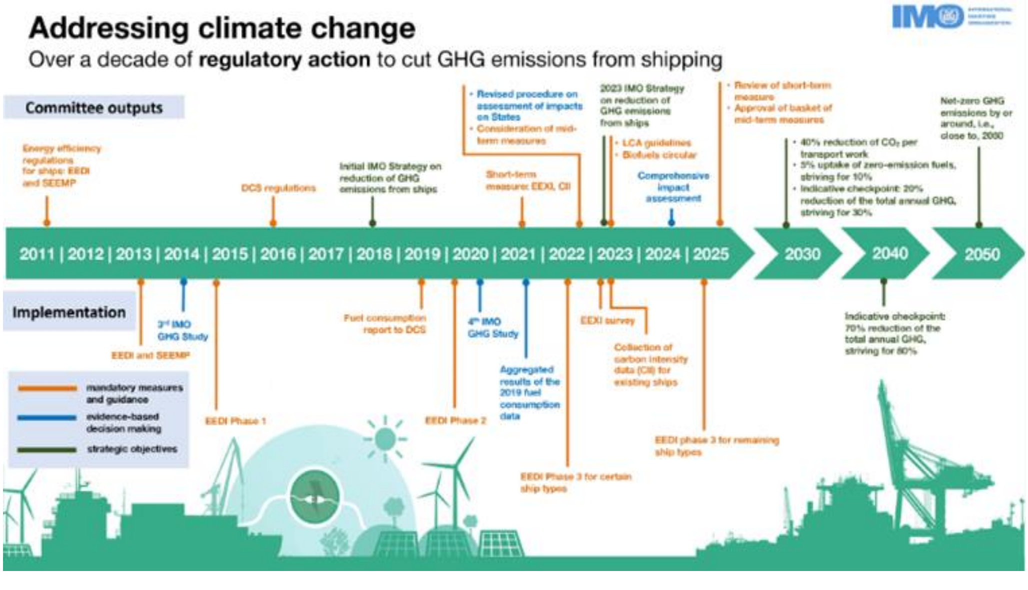


Fig. 8. History of GHG regulatory action from IMO [31]

The significance of flag states and port states in mitigating CO2 emissions is crucial within the scope of the resolutions adopted by the International Maritime Organization (IMO). Flag nations have a responsibility to ensure that ship operations comply with both national and international norms, as mandated by the IMO's emission reduction objectives and rules. Flag states have the ability to decrease

CO2 emissions by implementing more stringent emission regulations on ship owners and operators. Ports may enforce adherence to these criteria by performing inspections on vessels docking in their ports and promote environmentally friendly marine transportation by providing incentives to ships with low emissions. According to the decisions made by the International marine Organization (IMO), both flag states and port states have a crucial role in decreasing carbon dioxide (CO2) emissions in the worldwide marine industry. To achieve this, it is necessary to build efficient collaboration and regulatory frameworks [68][69].

5. System Dynamics Model for Ship GHG Emission

5.1 Model hypothesis

At global level, GHG emissions from ships and the rules developed to reduce these emissions are developed within the framework of IMO, EU and flag state policies. The impact of these emissions and the results of technical and operational measures on ship systems by developing global emission reduction policies bring IMO closer to the Net Zero Emission by 2050 targets.

In this project, CO2 emissions under the GHG emissions from ships at global level are considered for achieving detail understanding on the effect of their related factors. In this context, firstly, the overall dynamics, which increase and decrease the CO2 emissions from ships directly or indirectly, are identified for creating SD model. Following that in order to build mathematical equations, the relationships between all factors on CO2 emissions are defined. After identified mathematical equations, assumptions are needed to ensure the reliability and validity of the model and forecasting data by testing it via historical real data. At this point, CO2 emissions under the GHG emissions from container ships at global level are assumed in the SD model. This assumption is implemented due to the requirement of the SD model working principle. Because SD model works with real data, learns the behaviour from the data, and forecasts via developed model for future. Therefore, to implement the data on the simulation, scenarios should be assumed on the model. In the project, CO2 emission from container ships is considered as one of the scenarios for GHG emissions from ships. Additionally, maritime GHG refers to the greenhouse gas emissions produced by ships and other marine vessels in this project. GHGs emitted by maritime activities include high level CO2, and medium level Methane. The other GHGs types are emitted in very low level or non by maritime activities. Besides, by looking on the global GHGs, %79.7 CO2 takes place in the percentage pie. Therefore, CO2 is the critical GHGs, especially in maritime, so it is considered in this project due to the easy of the collect real data. However, the model should be considered a generic approach for GHG emission reduction by applying several scenarios.

For this purpose, in this project, the licensed Ventana Vensim Professional 2023 software as a SD model tool is used to create SD model for understanding CO2 emission changes under IMO emission reduction strategies. Additionally, Ventana Vensim training and consultancy services are utilized in this project in the scope of project fund. Besides, the project funding is used for meeting with partners at Shanghai Maritime Universitiy and attending IAMU AGA23 conference.

Based on the above consideration, the flow diagram for the project is as in Fig. 9.

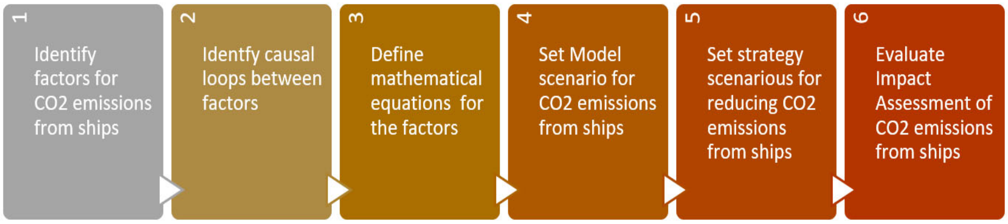


Fig. 9. Flow diagram for the project

5.1.1 Dynamics for ship CO2 emissions

Maritime GHGs

Maritime GHG refers to the greenhouse gas emissions produced by ships and other marine vessels. These emissions are significant contributors to global greenhouse gas levels, impacting climate change and environmental health. The primary greenhouse gases emitted by maritime activities include carbon dioxide (CO2), methane (CH4), and nitrous oxides (N2O), among others [32].

Carbon Dioxide (CO2): The primary GHG emitted by the maritime sector, resulting from the combustion of fossil fuels.

Methane (CH4): Can be emitted from the combustion or leakage of natural gas. Methane emissions may occur from ships using liquefied natural gas (LNG) as fuel.

The other GHGs such as N2O or Hydrofuorocarbons (HFCs) are emitted very low level or non by maritime activities.

In this project, only CO2 emissions are considered in the model due to the availability of the historical data for testing model validity and the criticality level in the maritime.

Reducing GHG emissions in maritime shipping is crucial in combating global climate change. The IMO’s targets and strategies have led to significant progress in the sector. Technological innovations and the adoption of alternative fuels are essential steps towards achieving a sustainable and low-carbon future in maritime transport.

Alternative Fuels and Consumption

Fuel consumption has a significant impact on GHG emission formation in the maritime sector as in all transport sectors. For this reason, alternative fuel types have been searched for different from traditional fuel types. For example, Methanol fuel use may significantly decrease sulfur oxide (SOx) emissions by 99%, nitrogen oxide (NOx) emissions by 18%, and particulate matter (PM) emissions by 99%, while also reducing carbon dioxide (CO2) emissions by 10% when compared to conventional fuels [65]. Regarding the implementation of alternative fuels and options, GHG emissions can be reduced through the introduction of alternative fuels such as electricity, biofuels and hydrogen [33]. The purpose of these regulation about the changing fuel type is to incentivize the shipping sector to transition towards using more efficient fuel types and decreasing energy usage, with the goal of reducing carbon emissions and pollutants. Simultaneously, the cyclical decline of the global economy and the high costs of fuel for ships need and demand that the shipping sector operates in a more efficient manner, while still meeting the needs of global commerce. Given that bunker fuel use, such as heavy fuel oil (HFO) and liquified natural gas (LNG), is the primary cause of emissions and represents a significant amount of operational expenses, shipping corporations are now undertaking extraordinary endeavors to enhance ship energy efficiency [34]. The distinctive feature of different potential alternative fuels is shown in Fig. 10 [35].

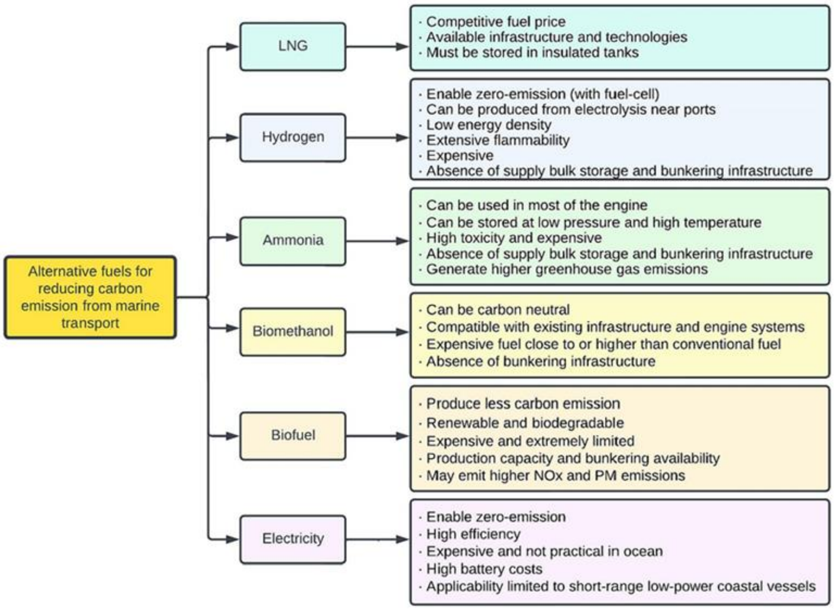


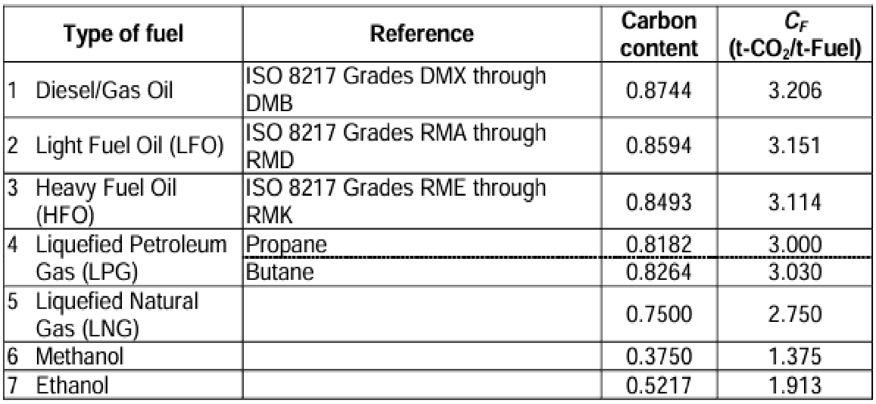
Fig. 10. The distinctive feature of different potential alternative fuels for the shipping industry [35]

Biofuel Blend

On the other hand, biofuel blends are considered the most feasible solution for mitigating shipping emissions. Bio-derived fuels are ecologically benign, renewable, and clean in comparison to the marine fuel oil and marine diesel presently in use. Moreover, their fuel properties and combustion characteristics closely resemble those of fossil fuels such as HFO, MDO, and LNG. The choice of alternative fuel and the extent to which it replaces conventional fuel will directly affect the emissions of the vessel, including GHG, nitrogen oxides (NOx), and sulfur oxides (SOx) [36].

Emission Factors for Fuels

Moreover, the carbon emissions released according to fuel types differ. Therefore, studies on the use of alternative fuels continue. Emission factor value is an important factor in carbon emission calculations according to fuel types. The calculation of CO2 emissions resulting from fuel use is based on the fuel emission factors outlined in 2014 Guidelines on the Method of Calculation of the Attained Energy Efficiency Design Index (EEDI) for New Ships, which are included in Fig. 11. The fuel emission factors determine the amount of carbon dioxide (CO2) released for every tons of fuel combusted in the engine [37].



Type of fuel	Reference	Carbon content	C_F (t-CO_2/t-Fuel)
1 Diesel/Gas Oil	ISO 8217 Grades DMX through DMB	0.8744	3.206
2 Light Fuel Oil (LFO)	ISO 8217 Grades RMA through RMD	0.8594	3.151
3 Heavy Fuel Oil (HFO)	ISO 8217 Grades RME through RMK	0.8493	3.114
4 Liquefied Petroleum Gas (LPG)	Propane	0.8182	3.000
	Butane	0.8264	3.030
5 Liquefied Natural Gas (LNG)		0.7500	2.750
6 Methanol		0.3750	1.375
7 Ethanol		0.5217	1.913

Fig. 11. Fuel emissions factor as indicated in Resolution MEPC.245(66) [37]

Well-to-Tank

Another significant factor is well-to-tank. The "well-to-tank" (WTT) process in the marine industry pertains to the greenhouse gas (GHG) emissions that arise from the extraction, manufacture, and transportation of fuel to a ship. These emissions have a significant influence on the total environmental impact of maritime operations. The significance of well-to-tank emissions is gaining prominence as alternative fuels such as biodiesel or hydrogen are increasingly being used, with emissions mostly occurring during the well-to-tank phase. Companies that aim to comprehend the actual consequences of their operations and conform to requirements from carbon accounting. Companies do this by using standardized emissions factors to translate fuel use into greenhouse gas emissions. Emissions factors, which are usually supplied by government entities or university research, are often expressed as a fixed numerical value for the emissions generated by the whole life cycle of a fuel, from production to consumption, or as a combined value for the entire process. These factors are applicable to various fuels such as diesel and gasoline. These characteristics are seldom mentioned with regard to the fuel's source or location of use [38].

Speed

Speed is identified as another influential component in the studies' analysis of greenhouse gas emissions. Ships have the ability to navigate at speeds that may vary from the speed stipulated in their design yet maintaining the same RPM (revolutions per minute), due to factors such as cargo circumstances and weather conditions. The emission formation is influenced by the actual speed value they achieve, which is dependent on all these parameters. Similarly, the varying deadweights of the ships have an impact on emission levels [39].

However, reducing speed is a very effective approach for minimizing carbon dioxide (CO2) emissions during ship operations. Carbon dioxide (CO2) is the primary greenhouse gas responsible for global warming and has enduring impacts on long-term climate change. On the other hand, emissions of Sulphur Oxide (SOX) result in acid rain and health issues. However, the effectiveness of speed reduction in reducing SOX emissions is limited since these emissions are influenced by the sulfur content of the fuel. Methane (CH4), although being a more powerful greenhouse gas than CO2, has a shorter atmospheric lifespan and is often emitted in greater quantities from the combustion of fuels like LNG. While lowering speed is really efficient in decreasing CO2 emissions, the management and control of these emissions may be better managed by the use of certain fuel types and technological techniques, as opposed to addressing SOX and CH4 [66] [67]. Speed reduction has a crucial role in limiting the long-term impacts of CO2 on global warming.

Deadweight

One of another significant factor for effecting the maritime GHG emission is deadweight. Emission values can be found by making calculations based on deadweight according to different ship types. However, it may not be correct to calculate the actual value of the cargo according to the deadweight value. Because, in reality the maximum cargo capacity, the payload, is lower than the dwt. Further, the load capacity utilization (LCU) should be considered. LCU is the value that expresses how much of the available ship capacity is used. Also, the fuel consumption (in mass of fuel per distance) of a given ship will depend on the load, since a heavier loaded ship will lie deeper and therefore encounter higher resistance from the water [40].

Emission Control Areas (ECAs)

By implementing higher emission restrictions, Emission Control Areas (ECAs) help regulate and reduce ship emissions in specified locations. These locations regulate sulfur oxides (SOx), nitrogen oxides (NOx), and particulate matter to reduce air pollution from shipping. ECA laws require ships to utilize greener fuels like low-sulfur fuel oil or LNG to decrease sulfur compound emissions. ECAs also encourage the use of pollution control technology like scrubbers systems to minimize NOx emissions. ECAs may also influence ship route decisions, promoting cleaner routes or rerouting to avoid them. ECAs greatly reduce area emissions, but emissions may transfer to surrounding regions, stressing the need to examine larger regional consequences. ECAs are essential for environmental preservation and sustainable transportation [41].

Carbon Tax

Furthermore, a carbon tax is an essential instrument for mitigating emissions in the maritime sector by the imposition of charges on carbon-based fuels, therefore incentivizing the business to embrace more environmentally friendly methods. The tax increase on these fuels serves as a motivation for strengthening the design and operating efficiency of ships. This may be achieved by the use of lighter materials, improving engine performance, and optimizing routes. In addition, it encourages a transition to cleaner fuels such as liquefied natural gas (LNG) and biofuels, leading to a further reduction in emissions. The tax further impacts consumer behavior by augmenting the expenses associated with long-distance transportation, resulting in a predilection for locally manufactured items. Furthermore, the income derived from carbon taxes might be allocated to support climate programs or research in clean technologies, promoting an ongoing cycle of environmental improvement. Carbon taxes enable a cost-effective method to achieve considerable reductions in marine emissions by making the cost of emission reductions equal across different mitigation measures [42].

Technological Impact

The evaluation emphasized the importance of various technologies and methods in lowering CO2 emissions in marine transport, highlighting their vital role in mitigating greenhouse gas emissions from the industry. Out of these technologies, the use of biofuels is particularly notable as a more sustainable substitute for conventional fossil fuels. It provides substantial reductions in CO2 emissions when employed in ship propulsion systems. Speed optimization is a crucial strategy since adjusting vessel speeds may result in significant fuel savings and reductions in emissions. This is because there is a direct correlation between speed and fuel use. Moreover, the use of energy-efficient ship design, which includes characteristics that minimize fuel usage, may substantially cut carbon dioxide emissions during the lifespan of a vessel. Waste heat recovery systems improve energy efficiency by recovering and reutilizing heat produced in ship power units. Furthermore, investigating alternate propulsion systems, such as LNG or hybrid systems, offers a practical approach to reducing CO2 emissions in comparison to conventional fuel combustion techniques. Together, these technologies and approaches are crucial tactics in the continuous endeavors to diminish the environmental consequences of the marine industry [43].

Fuel Costs

The expense of fuel plays a crucial element in the endeavors to diminish greenhouse gas (GHG) emissions in the marine sector. As the marine industry considers ways to shift towards cleaner and more sustainable fuels, the financial consequences of these alternatives become a critical consideration. Carbon-neutral fuels and emission reduction technologies show potential in addressing the environmental consequences of shipping. However, the broad implementation of these solutions depends on their price and accessibility. The use of low-carbon or carbon-neutral fuels may initially incur greater expenditures in comparison to typical fossil fuels, hence affecting the operating costs of shipping businesses. Nevertheless, with the progression of technology and the attainment of economies of scale in the manufacturing and dissemination of more environmentally friendly fuels, it is anticipated that the disparities in costs would diminish. Furthermore, the cost competitiveness of sustainable fuels may be influenced by legislative frameworks and market incentives, which might motivate the marine sector to invest in greener alternatives, even if there may be early financial repercussions. The cost of fuel significantly influences the tactics and rate at which GHG emissions are reduced in the marine industry, emphasizing the need to balance environmental objectives with economic factors [44].

Economic Growth

Macroeconomic considerations, such as GDP, will impact the intended load of global demand in the global system. As GDP rises, market demand will become more robust and less susceptible to charges such as transportation and fuel costs. The escalation of these fees will also have a negative impact on worldwide freight transportation and lead to a reduction in the demand for ships. Hence, the effect on greenhouse gas (GHG) emissions is an unavoidable reality [45].

5.2 Model Dynamics and Equations

The tool type, variable names, equations, variable units, definitions and dynamics references are listed specialized for container ships in Table 2. As mentioned before, this is presenting the parameters relevant to container ships as an application, but this approach can be used to model emissions from any segment, given the appropriate parameters.

Table 2. Model dynamics list

No	Tool Type	Variable Name	Equations	Unit	Definition	Reference
1	Stock	Fleet DWT	(1,69*10^8) + INTEG (New Ships DWT-Retired Ships DWT)	DWT	The total Deadweight Tonnage (DWT) of the fleet, representing the carrying capacity of all ships in the fleet.	[49]
2	Flow	New Ships DWT	Fleet DWT * Ship Building Rate	DWT/Year	The DWT of new ships added to the fleet.	[47]
3	Flow	Retired Ships DWT	Fleet DWT * Average Life Ship Span	DWT/Year	The DWT of ships that are retired from the fleet.	[47]
4	Variable	Ship Building Rate	Initial Shipbuilding Rate * (1+Technological Improvement Factor) * (1+Trade Volume Effect) * Calibration Factor	1/Year	The rate at which new ships are built.	[47]
5	Variable	Average Life Ship Span	30	Year	The average operational lifespan of ships in the fleet.	[47]
6	Variable	Technological Improvement Factor	0,03	Dmnl	A factor representing improvements in technology over time.	[52]
7	Variable	Initial Shipbuilding Rate	0,056	1/Year	The initial rate of shipbuilding at the start of the model period.	[51]
8	Variable	Trade Volume Effect	(Global Trade Volume / DELAY1 (Global Trade Volume, 1)) - 1	Dmnl	The impact of trade volume changes on the fleet and operations.	-
9	Stock	Global Trade Volume	(1,3*10^9) + INTEG (Global Trade Volume Change)	Loadston/Year	The total volume of global trade.	[46]
10	Flow	Global Trade Volume Change	Global Trade Volume * Economic Growth Rate	Loadston/Year	The rate of change in global trade volume.	-
11	Variable	Economic Growth Rate	Historical Data Imported	Dmnl	The rate of economic growth, influencing trade and shipping demand.	[47]
12	Variable	Global Voyage Number	Global Trade Volume / Average Annual Load	Dmnl	The total number of voyages made by the global fleet.	-
13	Variable	Average Annual Load	(Fleet DWT * Payload to DWT Ratio) * Load Capacity Utilization	Loadston	The average load carried by ships annually.	-
14	Variable	Payload to DWT Ratio	0,5	Loadston/DWT	The ratio of the actual payload to the ship’s DWT.	[54]

15	Variable	Load Capacity Utilization	0,47	Dmnl	The extent to which the fleet's carrying capacity is utilized.	[55]
16	Variable	Energy Consumption	(ME Average Load Factor + Average Load Factor of AE) * Sailing Time * Average Annual Load * PTR	KWh	The total energy consumption by the fleet.	-
17	Variable	Average Annual Distance Sailed	6000	mil	The average distance sailed by ships annually.	[48]
18	Variable	Sailing Time	Average Annual Distance Sailed * 0,9 / Ship Speed	hour	The total time spent sailing.	-
19	Variable	PTR	0,2	KW/Loadston	Propulsive thrust requirement, the force needed to move a ship through the water.	[64]
20	Variable	Ship Speed	20	knot	The average speed at which ships travel.	[53]
21	Variable	ME Average Load Factor	0,28 * (Ship Speed / 13,44) ^3	Dmnl	The average load factor of the main engine.	[51]
22	Variable	Average Load Factor of AE	0,17	Dmnl	The average load factor of auxiliary engines.	[51]
23	Variable	High Fuel Oil Consumption	Energy Consumption * sh HFO * Usage Ratio of HFO	Millionton	The consumption of high fuel oil by the fleet.	[51]
24	Variable	sh HFO	175*10^-10	Millionton/KWh	Specific fuel consumption value for low high sulphur fuel oil.	[50]
25	Variable	Usage Ratio of HFO	IF THAN ELSE (HFO Cost<LSFO Cost: AND: HFO Cost<MDO Cost: AND: HFO Cost<LNG Cost, f, e)	Dmnl	The usage ratio of high fuel oil.	[56]
26	Variable	High Fuel Emission Factor	3,545	Dmnl	The emission factor associated with high fuel oil.	[50]
27	Variable	HFO Emission	High Fuel Emission Factor * High Fuel Oil Consumption	Millionton	The total emissions from high fuel oil consumption.	-
28	Variable	LSFO Consumption	Energy Consumption * sh LSFO * Usage Ratio of LSFO Consumption	Millionton	The consumption of low sulphur fuel oil.	-
29	Variable	sh LSFO	167*10^-10	Millionton/KWh	Specific fuel consumption value for low sulphur fuel oil	[50]
30	Variable	Usage Ratio of LSFO Consumption	IF THAN ELSE (LSFO Cost<HFO Cost: AND: LSFO Cost<MDO Cost: AND: LSFO Cost<LNG Cost, c, d)	Dmnl	The usage ratio of low sulphur fuel oil.	[56]

31	Variable	LSFO Emission Factor	3,734	Dmnl	The emission factor associated with low sulphur fuel oil.	[50]
32	Variable	LSFO Emission	LSFO Consumption * LSFO Emission Factor	Millionton	The total emissions from low sulphur fuel oil consumption.	-
33	Variable	LNG Consumption	Energy Consumption * sh LNG * Usage Ratio of LNG Consumption	Millionton	The consumption of liquefied natural gas.	-
34	Variable	sh LNG	156*10^-10	Millionton/KWh	Specific fuel consumption value for liquefied natural gas.	[50]
35	Variable	Usage Ratio of LNG Consumption	IF THAN ELSE (LNG Cost<HFO Cost: AND: LNG Cost<MDO Cost: AND: LSFO Cost<LSFO Cost, a, b)	Dmnl	The usage ratio of liquefied natural gas.	[56]
36	Variable	LNG Emission Factor	3,28	Dmnl	The emission factor associated with liquefied natural gas.	[50]
37	Variable	LNG Emission	LNG Consumption * LNG Emission Factor	Millionton	The total emissions from liquefied natural gas consumption.	-
38	Variable	Diesel Oil Consumption	Energy Consumption * sh MDO * Usage Ratio of Diesel Oil	Millionton	The consumption of diesel oil.	-
39	Variable	sh MDO	165*10^-10	Dmnl	Specific fuel consumption value for marine diesel oil.	[50]
40	Variable	Usage Ratio of Diesel Oil	IF THAN ELSE (MDO Cost<HFO Cost: AND: MDO Cost<LNG Cost: AND: MDO Cost<LSFO Cost, a, b)	Dmnl	The usage ratio of diesel oil.	[56]
41	Variable	Diesel Oil Emission Factor	3,782	Dmnl	The emission factor associated with diesel oil.	[50]
42	Variable	MDO Emission	Diesel Oil Consumption * Diesel Oil Emission Factor	Millionton	The total emissions from diesel oil consumption.	-
43	Variable	Methanol Consumption	Energy Consumption * sh Methanol	Millionton	The consumption of methanol.	-
44	Variable	sh Methanol	0,186*10^-10	Millionton/KWh	Specific fuel consumption value for methanol.	[58]
45	Variable	Usage Ratio of Methanol	0,01	Dmnl	The usage ratio of methanol.	[56]
46	Variable	Methanol Emission Factor	1,375	Dmnl	The emission factor associated with methanol.	[2]

47	Variable	Methanol Emission	Methanol Consumption * Methanol Emission Factor * Usage Ratio of Methanol	Millionton/KWh	The total emissions from methanol consumption.	-
48	Variable	Ammonia Consumption	Energy Consumption * sh Ammonia	Millionton	The consumption of ammonia.	-
49	Variable	sh Ammonia	0,194*10^-10	Millionton/KWh	Specific fuel consumption value for ammonia.	[58]
50	Variable	Usage Ratio of Ammonia	0,01	Dmnl	The usage ratio of ammonia.	[56]
51	Variable	Ammonia Emission Factor	1,6	Dmnl	The emission factor associated with ammonia.	[57]
52	Variable	Ammonia Emission	Ammonia Consumption * Ammonia Emission Factor * Usage Ratio of Ammonia	Millionton/KWh	The total emissions from ammonia consumption.	-
53	Variable	a	0	Dmnl	Usage ratio	-
54	Variable	b	0,1	Dmnl	Usage ratio	-
55	Variable	c	0,2	Dmnl	Usage ratio	-
56	Variable	d	0,3	Dmnl	Usage ratio	-
57	Variable	e	0,6	Dmnl	Usage ratio	-
58	Variable	f	0,8	Dmnl	Usage ratio	-
59	Variable	CO2 Emission Without tr	(HFO Emission + LSFO Emission + LNG Emission + MDO Emission + Ammonia Emission + Methanol Emission) - Fleet DWT * EEDI Effect	Millionton	The total CO2 emissions from all fuel types without CO2 emission treatment.	-
60	Variable	Decrease Rate	(CO2 Emission-CO2 Emission Without tr)/CO2 Emission Without tr	Dmnl	The rate of decrease in CO2 emissions.	-
61	Flow	CO2 Emission	(HFO Emission + LSFO Emission + LNG Emission + MDO Emission + Ammonia Emission + Methanol Emission) - Fleet DWT * EEDI Effect	Millionton	The total CO2 emissions from all fuel types.	[51]
62	Stock	Marine Fleet CO2 Emission	0,277 + INTEG (CO2 Emission)	Millionton	The total CO2 emissions from the entire marine fleet.	[48]
63	Variable	Carbon Tax Rate	50	$/ton	The rate of carbon tax.	[51]
64	Variable	Additional Fuel Cost	IF THAN ELSE (Time<2024, 0, Carbon Tax Rate * CO2 Emission * 100)		Additional cost due to carbon tax on CO2 emissions.	[51]
65	Variable	HFO Cost	500	$/ton	The cost of high sulphur fuel oil.	[59]
66	Variable	LSFO Cost	600	$/ton	The cost of low sulphur fuel oil.	[59]

67	Variable	MDO Cost	700	$/ton	The cost of marine diesel oil.	[59]
68	Variable	LNG Cost	800	$/ton	The cost of liquefied natural gas.	[60]
69	Variable	Methanol Cost	300	$/ton	The cost of methanol.	[61]
70	Variable	Ammonia Cost	200	$/ton	The cost of ammonia.	[62]
71	Variable	Total Fuel Cost	(HFO Cost * High Fuel Oil Consumption + LNG Cost * LNG Consumption + LSFO Cost * LSFO Consumption + MDO Cost * Diesel Oil Consumption) *100 + Additional Fuel Cost + Methanol Consumption * Methanol Cost + Ammonia Consumption * Ammonia Cost	$	The total cost of all types of fuel consumed, including additional costs due to carbon tax.	[51]
72	Variable	EEDI Effect	IF THAN ELSE (Time<2024, 0, 1,7*10^-7)	Millionton/DWT	The effect of the Energy Efficiency Design Index (EEDI) regulation on emissions.	[63]

(DWT: Deighweight , Dmnl: Dimensionless, Loadston: Loaded tons, KWh: Kilowatt-hour, $: Dollars)

The causes trees of the main dynamics are given in Fig.12, Fig.13, Fig.14, Fig.15.

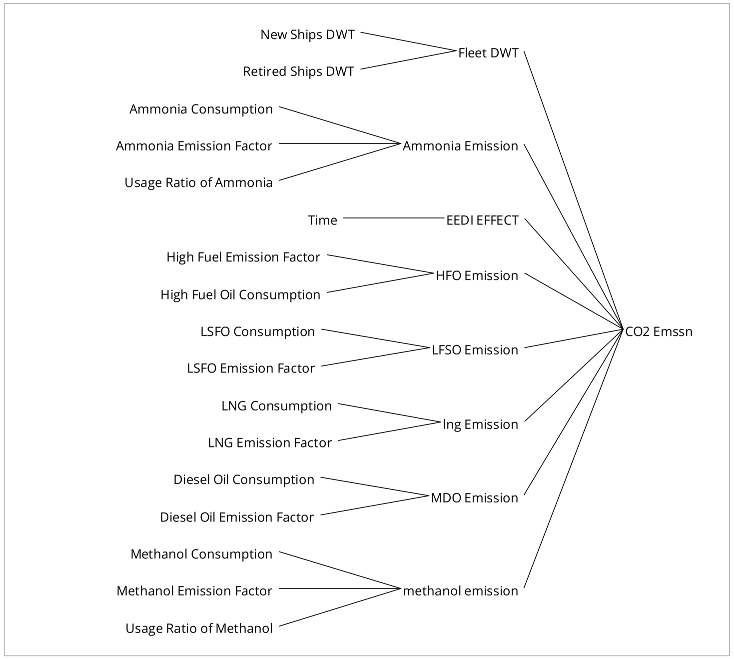


Fig.12 CO2 Emission Cause Tree

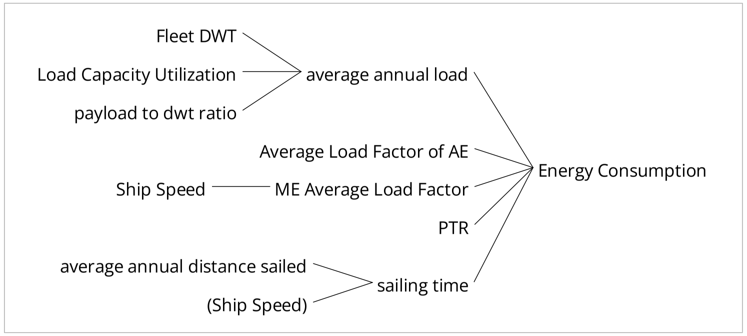


Fig.13 Energy Consumption Cause Tree

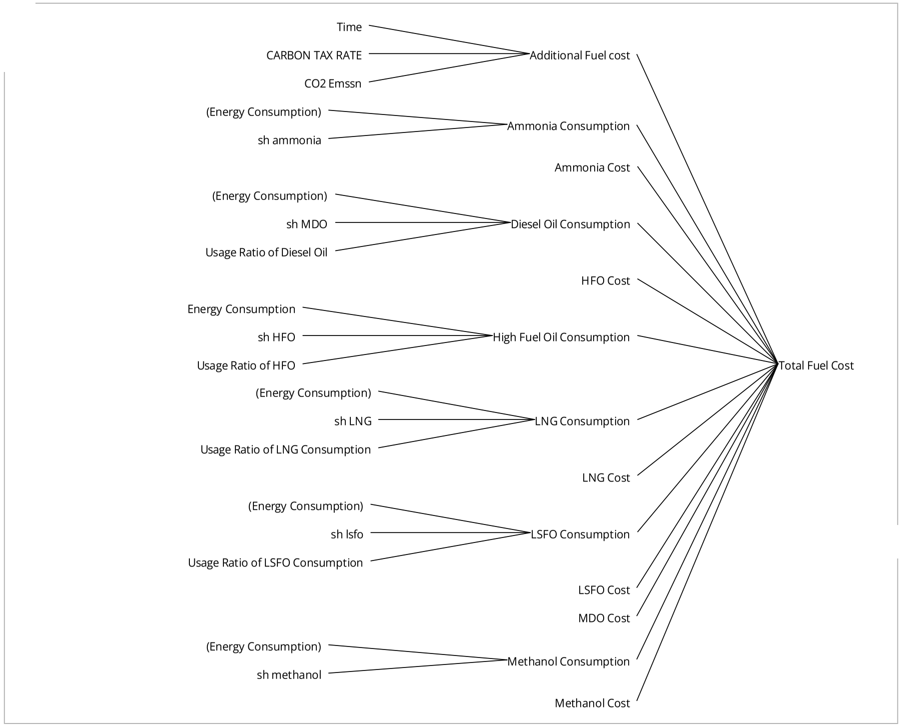


Fig.14 Total Fuel Cost Cause Tree

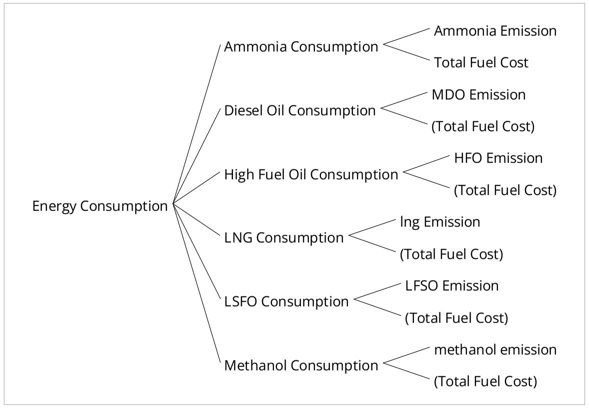


Fig.15 Energy Consumption Effect Tree

5.3 Data Collection

The historical data used in this project is shown in this section. In the base model, the data for seaborne trade, maritime trade growth, total carbon dioxide emissions by vessels, deadweight of the vessels, distance travelled of maritime cargo, fuel consumption by vessels, carbon contents of the fuel types, well to wake of the fuel types are obtained as in Fig. 16 [46], Fig. 17 [47], Fig. 18 [48], Fig. 19 [49], Fig. 20 [48], Fig. 21 [2], Fig. 22 [50] and Fig. 23 [50] respectively.

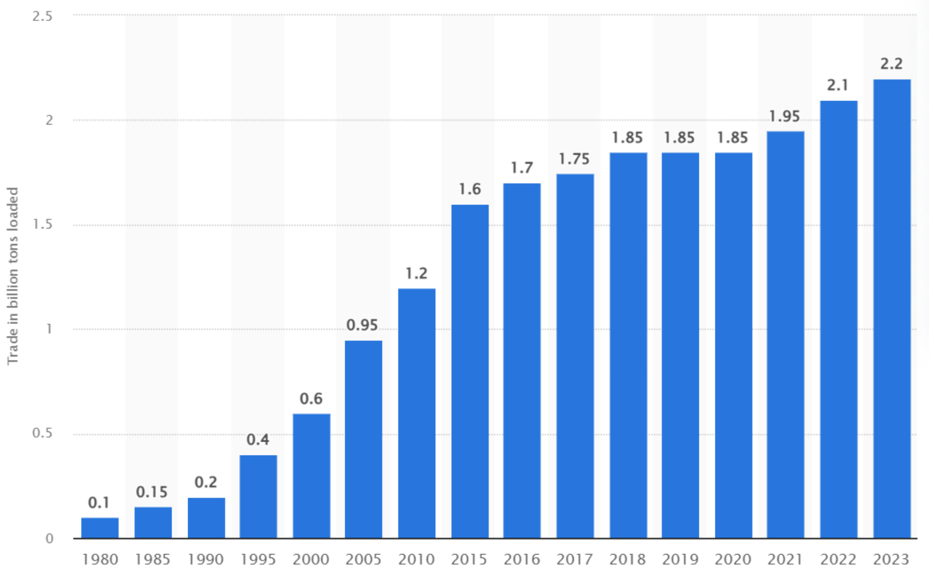


Fig. 16. International seaborne trade carried by container ships from 1980 to 2023 (in billion tons loaded) [46]

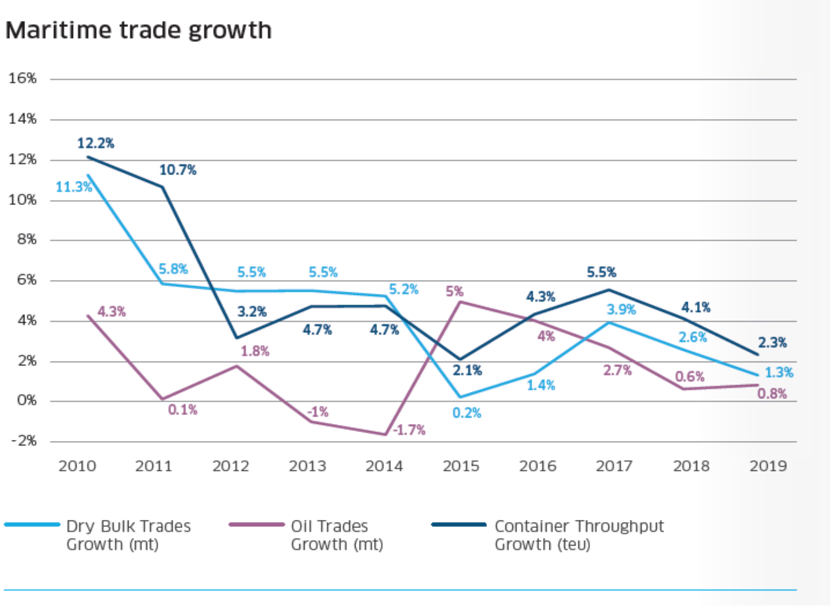


Fig. 17. Maritime trade growth [47]

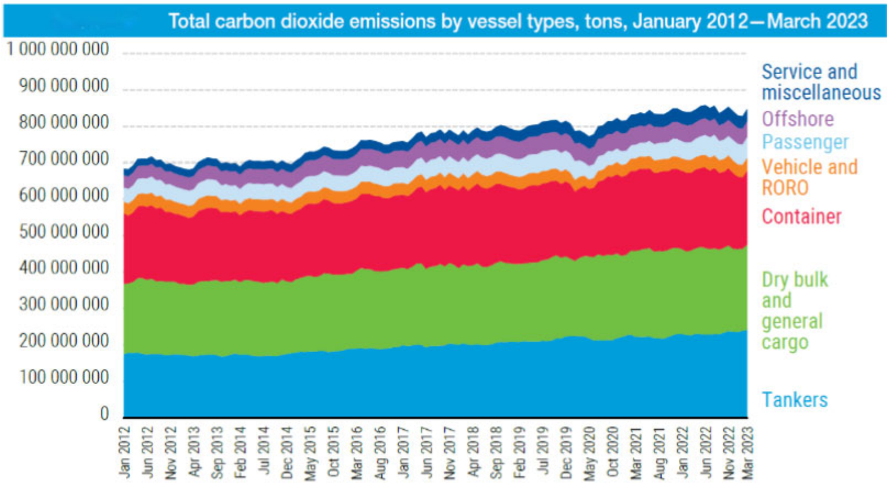


Fig. 18. Total CO2 emissions by vessel types between 2012-2023 [48]

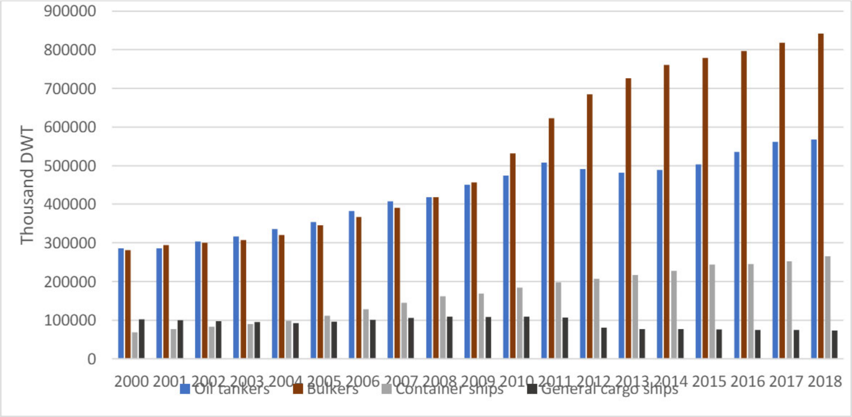


Fig. 19. Deadweight of four main types of cargo ships during 2000-2018 [49]

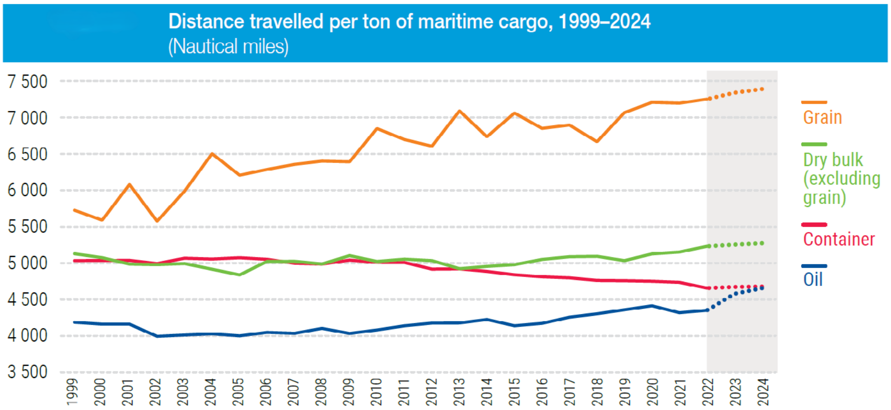
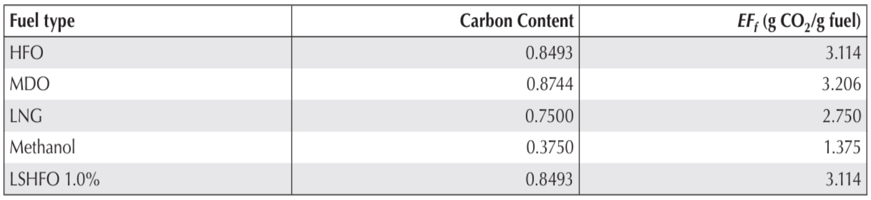
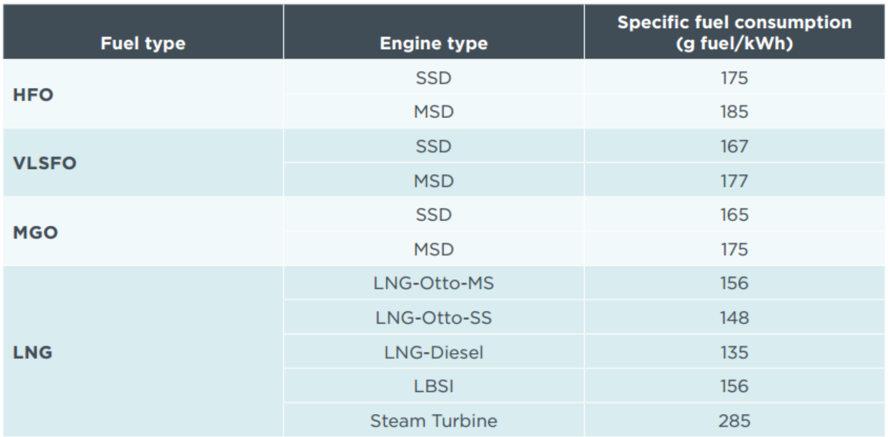


Fig. 20. Distance travelled per ton of maritime cargo [48]



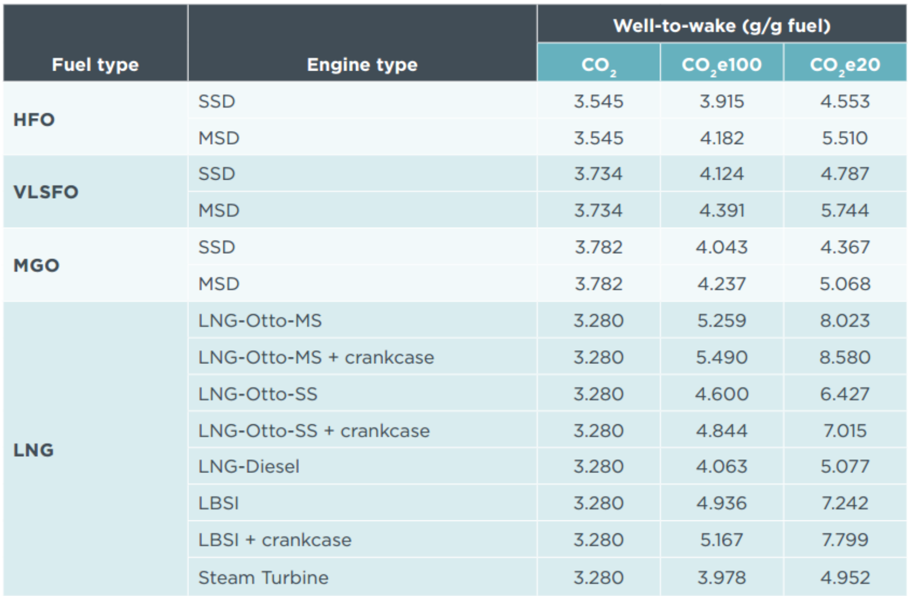
Fuel type	Carbon Content	EF_f (g CO_2/g fuel)
HFO	0.8493	3.114
MDO	0.8744	3.206
LNG	0.7500	2.750
Methanol	0.3750	1.375
LSHFO 1.0%	0.8493	3.114

Fig. 21. Carbon emission factor for different type of fuels [2]



Fuel type	Engine type	Specific fuel consumption (g fuel/kWh)
HFO	SSD	175
	MSD	185
VLSFO	SSD	167
	MSD	177
MGO	SSD	165
	MSD	175
LNG	LNG-Otto-MS	156
	LNG-Otto-SS	148
	LNG-Diesel	135
	LBSI	156
	Steam Turbine	285

Fig. 22. Specific fuel consumption (g/kWh) for marine engines [50]



Fuel type	Engine type	Well-to-wake (g/g fuel)		
		CO_2	CO_2e100	CO_2e20
HFO	SSD	3.545	3.915	4.553
	MSD	3.545	4.182	5.510
VLSFO	SSD	3.734	4.124	4.787
	MSD	3.734	4.391	5.744
MGO	SSD	3.782	4.043	4.367
	MSD	3.782	4.237	5.068
LNG	LNG-Otto-MS	3.280	5.259	8.023
	LNG-Otto-MS + crankcase	3.280	5.490	8.580
	LNG-Otto-SS	3.280	4.600	6.427
	LNG-Otto-SS + crankcase	3.280	4.844	7.015
	LNG-Diesel	3.280	4.063	5.077
	LBSI	3.280	4.936	7.242
	LBSI + crankcase	3.280	5.167	7.799
	Steam Turbine	3.280	3.978	4.952

Fig. 23. Well-to-wake carbon dioxide and carbon dioxide equivalent factors for fossil marine fuels [50]

5.4 SD Model Framework

Fig. 24 shows the system dynamic model framework for maritime CO2 emissions scope of this project.

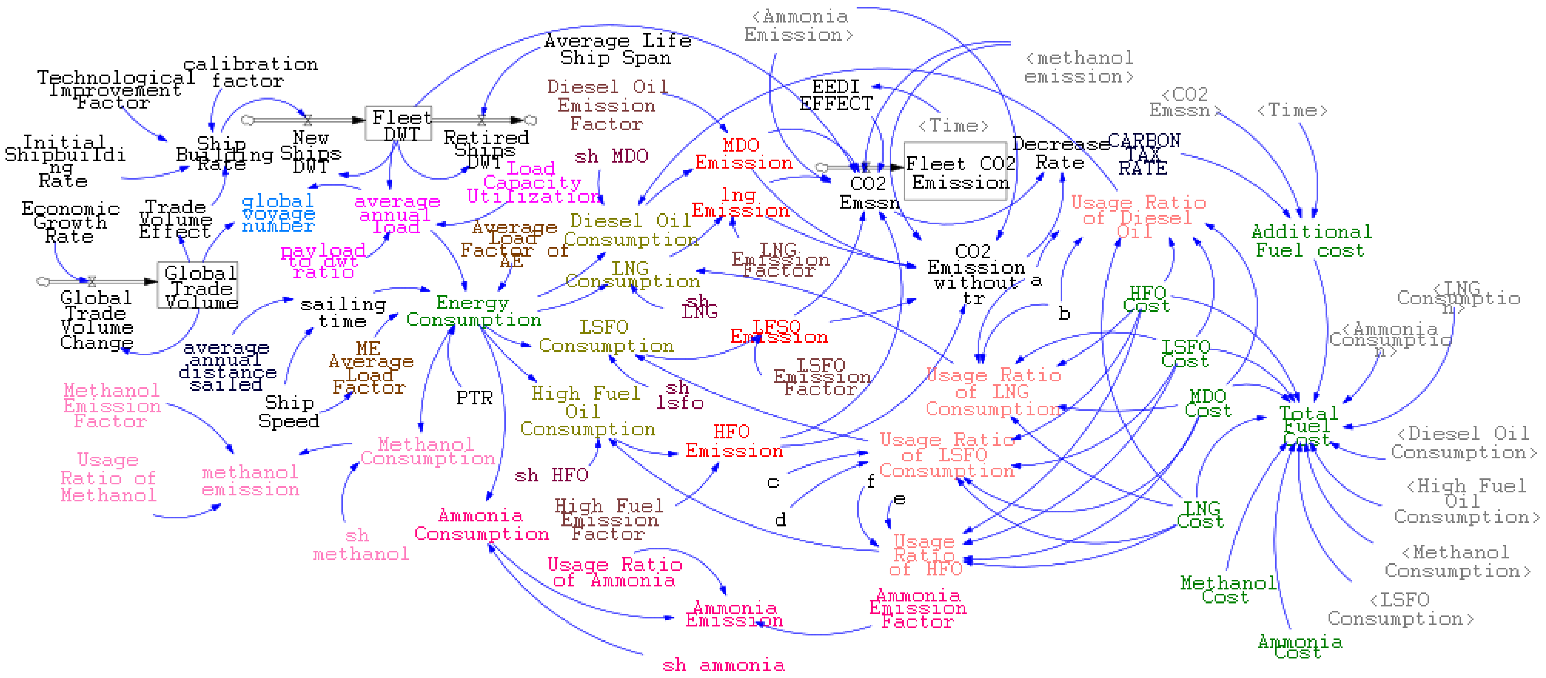


Fig. 24. The system dynamic model framework for maritime CO2 emission

6. SD Model Analysis and Impact Assessment

Base Scenario: Base scenario is created by assuming "CO2 emissions from container ships with the exist applications on the ships without any emission reduction strategies".

The SD model framework of base scenario is as in Fig. 25.

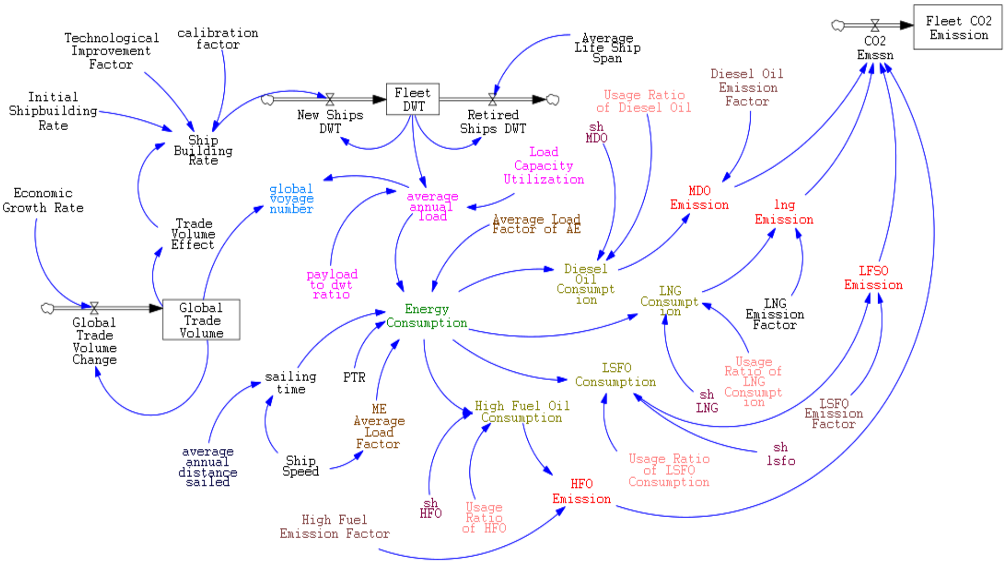


Fig. 25. SD model framework of base scenario

The constant values for the dynamics used in base scenario are shown in Table 3.

Table 3. Values for base scenario

Dynamics	Value	Unit	Reference
Technological improvement factor	0.03	dmnl	[52]
Initial shipbuilding rate	0.056	1/year	[51]
Average annual distance sailed	6000	mil	[48]
Ship speed	23	knot	[53]
Payload to DWT	0.5	loadston/dwt	[54]
Load capacity utilization	0.47	dmnl	[55]
HFO emission factor	3.545	CO2ton/fuelton	[50]
Usage ratio of HFO	0.8	dmnl	[56]
LSFO emission factor	3.734	CO2ton/fuelton LSFO	[50]
Usage ratio of LSFO	0.2	dmnl	[56]
LNG emission factor	3.28	CO2ton/fuelton LNG	[50]
Diesel oil emission factor	3.782	CO2ton/fuelton Dieseloil	[50]
Average load factor of AE	0.17	dmnl	[51]
Average load factor of ME (coefficient)	0.28	dmnl	[51]
Average life ship span	30	year	[47]

This scenario is designed to verify model validity while also comprehending future CO2 emissions from container ships if no CO2 emission reduction methods are implemented by the maritime sector. The results of the values for the CO2 emissions and the fleet deadweights (DWT) of the container ships are as in Fig. 26 and Fig. 27, respectively. Accordingly, the real data for the CO2 emissions from container ships between 2019-2020 and the base scenario model are consistent. Similarly, the validity of the model is also ensured by checking fleet DWT. The real data and base scenario model for fleet DWT are also coherent with very little deviation. As a result, the validity of the model is obtained in this project.

Besides, it is understood from the base scenario that if the absence of reduction strategies for GHG occurs (If the maritime industry continues with its current practices for GHG emissions), the forecasting for CO2 emissions is 278 m tons in 2030 and 712 m tons in 2050.

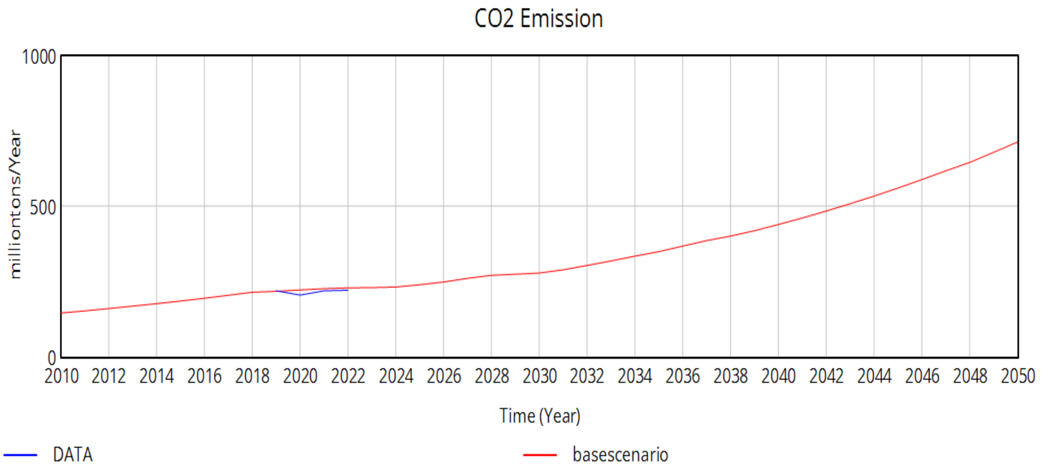


Fig. 26. Results for CO2 emissions from container ships in the base scenario model

Fig. 27. Results for Fleet DWT for container ships in the base scenario model

7. Scenario Development for Maritime GHG Emissions

7.1 SD Framework

The International Maritime Organization (IMO) has developed a versatile strategy to reduce the greenhouse gas (GHG) emissions in the maritime sector. At the center of this strategy, the adoption of various fuel options such as liquefied natural gas (LNG), heavy fuel (HFO), Marine Diesel Oil (MDO), low sulfur fuel oil (LSFO), ammonia and methanol. Each of these fuels offers different advantages and difficulties in terms of emission reduction, discovery and infrastructure requirements. For example, LNG produces lower CO2 emissions compared to traditional HFO, while MDO and LSFO helps to reduce sulfur oxides (SOX) and particle substance emissions. When produced from renewable sources, ammonia and methanol stand out as the prominent alternatives with its potential for carbon emissions near zero. IMO's strategy not only supports the adoption of these alternative fuels, but also integrates the energy efficiency design index (EEDI) and carbon density indicator (CII) (CII) and aims to maintain continuous improvement in global fleet energy efficiency and emission reduction. The IMO aims to significantly reduce the environmental impact of the maritime sector and to contribute to global GHG reduction goals by promoting various energy mixture and applying strict efficiency standards.

Based on these strategies, a new SD model framework is designed by adding the dynamics for GHG strategies into the base scenario as in Fig. 28.

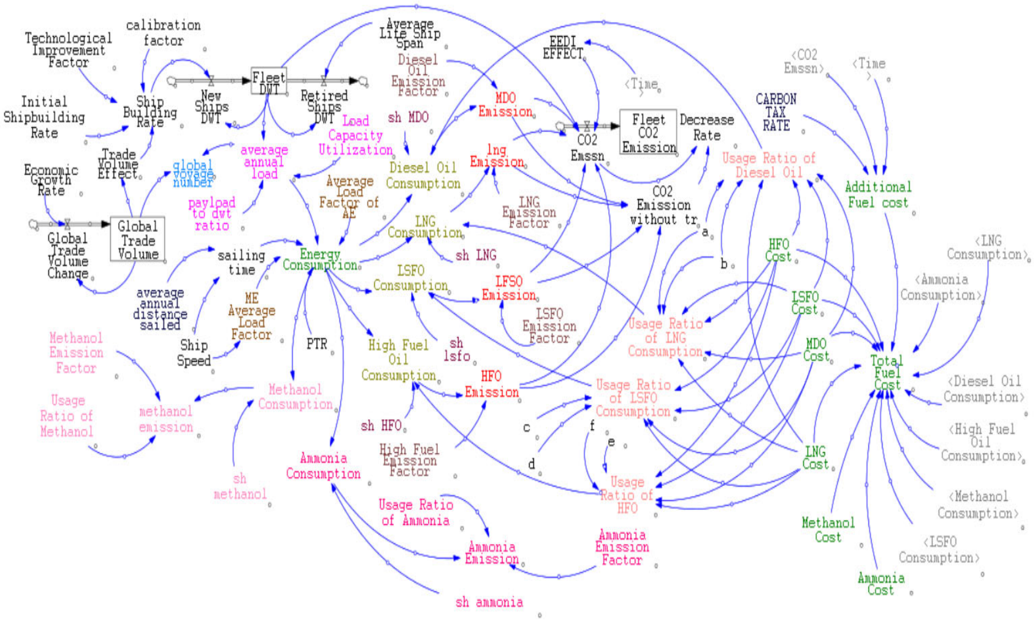


Fig. 28. SD model framework for scenarios with IMO GHG strategies

The constant values for the dynamics used in strategy scenarios that are different from base scenario shown in Table 4.

Table 4. Values for base scenario

Dynamics	Value	Unit	Reference
Ammonia emission factor	1.6	CO2ton/fuelton ammonia	[57]
Specific heat consumption of ammonia	0.194	tons/kwh	[58]
Methanol emission factor	1.375	CO2ton/fuelton methanol	[2]
Specific heat consumption methanol	0.183	tons/kwh	[58]
HFO Cost	500	$/fuelton for considered type	[59]
LSFO Cost	600	$/fuelton for considered type	[59]
MDO Cost	700	$/fuelton for considered type	[59]
LNG Cost	800	$/fuelton for considered type	[60]
Methanol Cost	300	$/fuelton for considered type	[61]
Ammonia Cost	200	$/fuelton for considered type	[62]
EEDI	0.17	tons/dwt	[63]

7.2 Developed Scenarios and Findings

Three scenarios are developed from the scope of the project.

Scenario (i)

i. For understanding change in fuel usage attitude of the shipping sector.

The parameters for (i) scenario are shown in Table 5.

Table 5. Type of scenarios and parameters

Scenarios	Usage Ratio of HFO	Usage Ratio of MDO	Usage Ratio of LSFO	Usage Ratio of LNG	Usage Ratio of Ammonium	Usage Ratio of Methanol	EEDI EFFECT	Carbon Tax	Speed (knots)
Scenario i-Business as Usual	0.8	0	0.2	0	0	0	X	-	23
Scenario ii-IMO based	0.65	0.1	0.1	0.1	0.025	0.025	X	50	18
Scenario iii-Aggresive	0	0	0.2	0.3	0.25	0.25	X	50	15

The overall result of (i) scenario is shown as in Fig. 29 and the values of the C02 emission changes are shown in Table 6. According to the results shown in Fig. 29, it is seen that there is a sharp increase trend from 2025 until 2030 and 2050 when no GHG reduction strategy is applied on GHG emissions from ships.

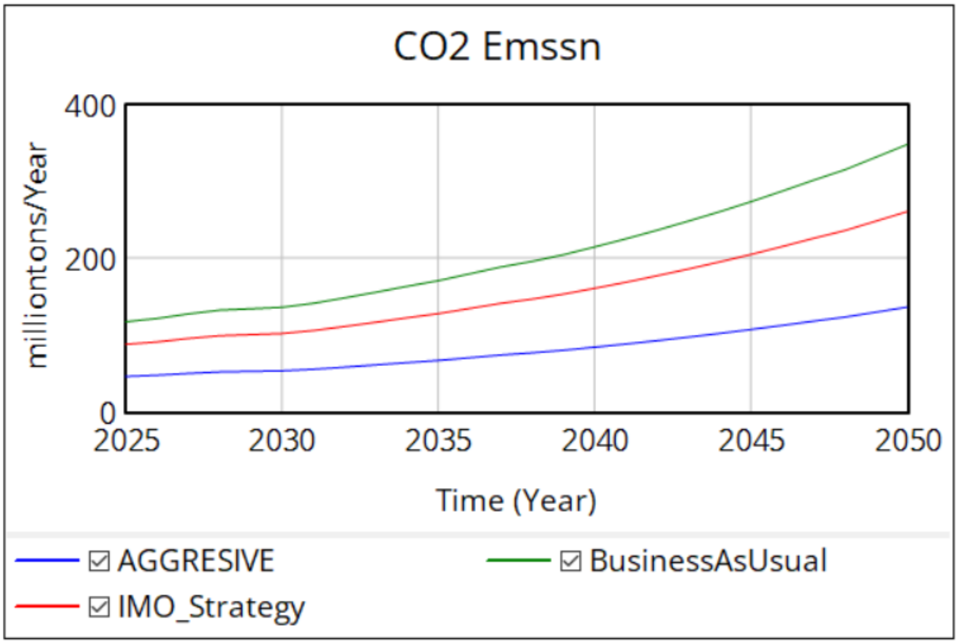
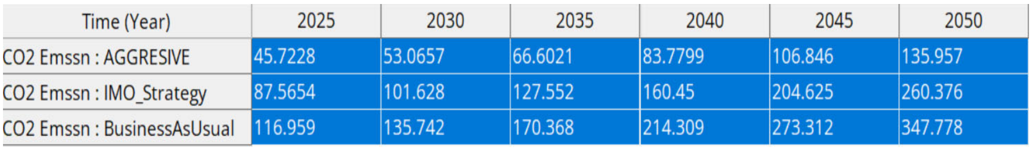


Fig. 29. The result of (i) scenario

Table 6. The result of (i) scenario – Change of CO2 Emission (million tons CO2 per year)



Time (Year)	2025	2030	2035	2040	2045	2050
CO2 Emssn : AGGRESIVE	45.7228	53.0657	66.6021	83.7799	106.846	135.957
CO2 Emssn : IMO_Strategy	87.5654	101.628	127.552	160.45	204.625	260.376
CO2 Emssn : BusinessAsUsual	116.959	135.742	170.368	214.309	273.312	347.778

Findings for Scenario(i)

In the scenario (i), in scenario 1 – Business As Usual, the trend on the CO2 emission is that Emissions increase steadily and sharply, reaching the highest value of 347,778 units by 2050. This scenario reflects the consequences of continuing current practices without additional measures to address GHG emissions. The sharp increase highlights the importance of implementing effective mitigation strategies, as this path leads to the highest emissions, exacerbating climate change impacts.

In scenario 2 – IMO-Strategy, the trend on the CO2 emission is that Emissions gradually increase over time, peaking in 2047 at 247,996 units, then slightly decreasing towards 2050 at 260,376 units. This scenario likely represents the current and planned strategies by the International Maritime Organization (IMO) to mitigate GHG emissions. Although there is a significant increase over time, the peak and slight reduction indicate some effectiveness of the strategies but not enough to significantly curb emissions growth.

In scenario 3 – Aggressive Strategy, the trend on the CO2 emission is that Emissions also increase over time but at a slower rate compared to the IMO strategy. Emissions in 2050 are 135,957 units, significantly lower than the IMO_Strategy. This scenario suggests more stringent measures and aggressive policies to reduce CO2 emissions. The slower growth and lower overall emissions show the potential impact of implementing more aggressive decarbonization measures in the maritime industry.

This scenario could include stricter regulations, advanced technologies, and significant shifts to greener fuels.

For the key points of scenario (i), the BusinessAsUsual scenario results in the highest emissions, while the Aggressive scenario shows the lowest, demonstrating the critical need for more aggressive policies and strategies. In terms of policy impact, the data highlights the impact of policy interventions. The IMO Strategy, while better than BusinessAsUsual, still shows significant emissions growth, indicating room for improvement. In terms of long-term outlook, the long-term projections stress the importance of sustained and enhanced efforts in emission reduction to achieve significant mitigation of climate change impacts.

As a result, it is concluded that recommendations for CO2 emission reduction are strengthen IMO policies, adopt aggressive measures, continuous monitoring and adjustment.

- Strengthen IMO Policies: Given the modest effectiveness of current IMO strategies, there is a need to strengthen and possibly accelerate the implementation of these policies.
- Adopt Aggressive Measures: The significant reduction in emissions in the Aggressive scenario suggests that adopting more aggressive measures is crucial.
- Continuous Monitoring and Adjustment: Regularly monitor emissions and adjust strategies to ensure that targets are met and new technologies or practices are integrated promptly.

Scenario (ii)

ii. For understanding change in speed attitude of the shipping sector

The result of (ii) scenario is shown as in Fig. 30 and the values of the C02 emission changes are shown in Table 7. In this scenario, the speed value, which is set 23 knots in the base setting, is changed as 18 knot and 15 knots.

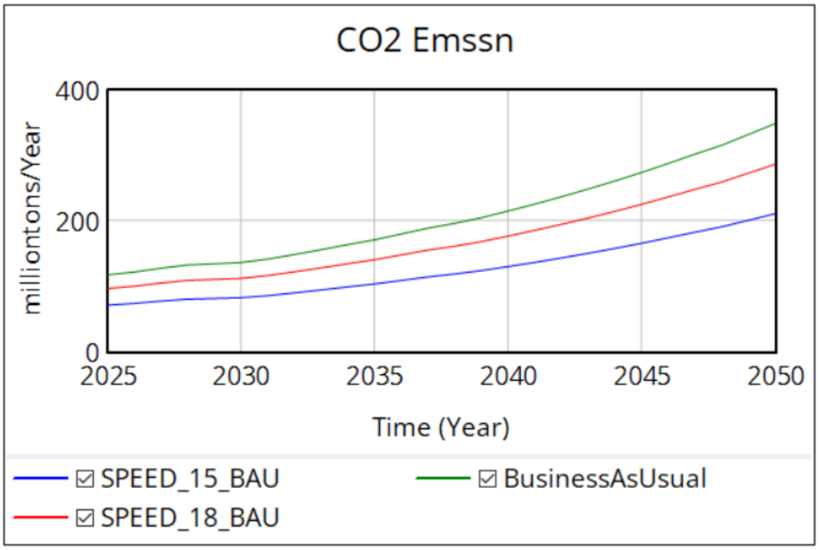
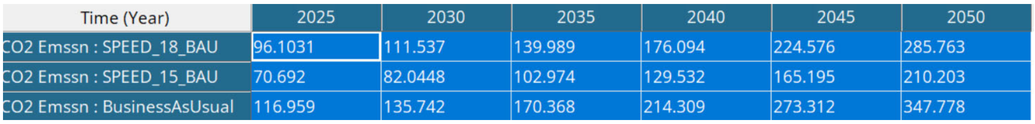


Fig. 30. The result of (ii) scenario

Table 7. The result of (ii) scenario – Change of CO2 Emission (million tons CO2 per year)



Time (Year)	2025	2030	2035	2040	2045	2050
CO2 Emssn : SPEED_18_BAU	96.1031	111.537	139.989	176.094	224.576	285.763
CO2 Emssn : SPEED_15_BAU	70.692	82.0448	102.974	129.532	165.195	210.203
CO2 Emssn : BusinessAsUsual	116.959	135.742	170.368	214.309	273.312	347.778

Findings for Scenario(ii)

The second set of data from your system dynamics model illustrates the impact of different ship speeds on CO2 emissions under a Business as Usual (BAU) scenario. By discussing these findings, particularly focusing on the impact of speed reduction, which is an important measure considered by the International Maritime Organization (IMO), the results are as following. When speed is 15 knots, emissions show a gradual increase from 70,692 units in 2025 to 210,203 units in 2050. This scenario represents a situation where ship speeds are reduced to 15 knots under a BAU context. The lower speed results in significantly lower emissions compared to the BusinessAsUsual scenario.

By assuming the speed as 18 knots, emissions start at 961,031 units in 2025 and increase to 285,763 units by 2050. This scenario models the emissions at a slightly higher speed of 18 knots. Emissions are still lower than the BusinessAsUsual scenario but much higher than the Speed_15_BAU scenario.

In the BusinessAsUsual scenario, which the speed is 23 knots, emissions increase from 116,959 units in 2025 to 347,778 units by 2050. This scenario reflects the emissions if current practices continue without any speed reductions or other significant interventions. It represents the highest emission path among the three scenarios.

The Key Points in the scenario(ii) are that;

- Speed Reduction Impact: The data clearly shows that reducing ship speeds has a significant impact on CO2 emissions. Lower speeds (15 knots) result in substantially lower emissions compared to maintaining higher speeds (18 knots) or the BusinessAsUsual scenario.
- Policy Implications: The IMO could consider enforcing speed reduction as a viable strategy to reduce emissions. The data supports the effectiveness of such measures, indicating that even moderate speed reductions can lead to considerable emission reductions.
- System Dynamics Modelling: Your use of system dynamics modelling provides a valuable tool for understanding the long-term impacts of different strategies on CO2 emissions. It helps in visualizing the outcomes of various scenarios and supports decision-making for policy and regulation development.

Recommendations obtained from scenario (ii) are as follows:

- Implement Speed Regulations: The IMO should consider implementing or tightening speed regulations to achieve lower emissions. This could be part of a broader strategy that includes technological advancements and operational efficiencies.
- Further Research and Monitoring: Continuous research and monitoring of emissions are crucial. Adjusting models and strategies based on new data and technological advancements will help in achieving long-term sustainability goals.
- Integrated Approach: Combining speed reduction with other measures, such as improving fuel efficiency and adopting cleaner technologies, will be essential to meet global emission targets.

Scenario (iii)

i. For understanding change in increasing attitude of the cost of HFO and decreasing attitude of the cost of LNG in the shipping sector

The result of (iii) scenario is shown as in Fig. 31. and the values of the C02 emission changes are shown in Table 8. In this scenario, the cost of HFO is increased in the rate of 65 percent of the cost of LNG.

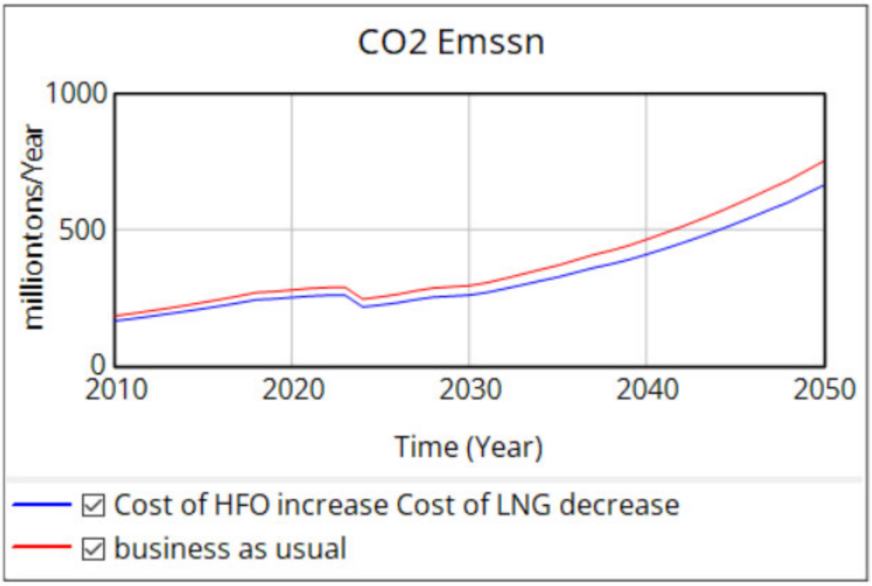


Fig. 31. The result of (iii) scenario

Table 8. The result of (iii) scenario – Change of CO2 Emission (million tons CO2 per year)

Time (Year)	2025	2030	2035	2040	2045	2050
CO2 Emssn : Cost of HFO increase Cost of LNG decrease_BAU	87.5727	101.636	127.563	160.463	204.642	260.398
CO2 Emssn : BusinessAsUsual	116.959	135.742	170.368	214.309	273.312	347.778

Findings for Scenario(iii)

In scenario (iii), emissions start at 87.5727 units in 2025 and gradually increase to 260.398 units by 2050. This scenario demonstrates the potential impact of economic factors on emissions. By increasing the cost of HFO and decreasing the cost of LNG, there is a significant reduction in CO2 emissions compared to the BusinessAsUsual scenario. This is likely due to a shift from HFO to LNG as a more cost-effective fuel option, which results in lower CO2 emissions.

In Business As Usual Scenario, emissions increase from 116.959 units in 2025 to 347.778 units by 2050. This scenario reflects the highest emissions pathway, indicating no change in the current practices and fuel usage. The continuous rise in emissions highlights the urgency for implementing effective mitigation strategies.

Key Points for the scenario (iii) are as following. The scenario where HFO prices increase and LNG costs decrease shows a clear reduction in emissions. This indicates that economic incentives and market mechanisms can effectively drive a shift towards cleaner fuels. Policymakers, including the IMO, could leverage such economic strategies to promote the adoption of lower-emission fuels. By adjusting taxes, subsidies, and regulations to make cleaner fuels more financially attractive, significant emissions reductions can be achieved. The gradual increase in emissions in the HFO price increase, LNG cost decrease scenario still underscores the need for continuous improvement and additional measures beyond just economic incentives to ensure long-term sustainability.

7.3 Discussion

This research created three scenarios to evaluate the consequences of different tactics used to decrease greenhouse gas (GHG) emissions in the marine industry. The first scenario investigated the impact of fuel consumption choices on emissions. According to the findings, if present habits persist, there would be a consistent and significant rise in CO2 emissions between 2025 and 2050. This discovery emphasizes the insufficiency of current greenhouse gas (GHG) mitigation efforts and emphasizes the need for more efficient approaches. Although the existing measures used by the International Maritime Organization (IMO) do result in a certain level of emission reduction, this decline is inadequate. The example illustrates the need of using more assertive tactics in order to effectively decrease CO2 emissions in the marine industry.

The second scenario investigated the influence of changes in ship velocities on CO2 emissions. The results indicate that decreasing the speed of ships results in a substantial reduction in emissions. Specifically, ships traveling at a speed of 15 knots generate significantly reduced emissions in comparison to other situations. This result implies that the International Maritime Organization (IMO) should consider implementing speed limitations as a feasible approach to decrease emissions. Emissions at a moderate velocity of 18 knots are lower than at the maximum velocity of 23 knots. However, the scenario indicates that more decreases in speed might be more efficient in reducing emissions. This suggests that implementing speed limitations has the potential to be an effective strategy for decreasing emissions in the marine industry.

The third scenario included analyzing the impact of rising heavy fuel oil (HFO) prices and falling liquefied natural gas (LNG) costs on fuel choices. According to the findings, an increase in HFO prices and a decrease in LNG costs lead to a transition in the marine industry towards more environmentally friendly fuels, resulting in a significant decrease in CO2 emissions. This discovery implies that financial rewards and market processes may successfully promote the use of more environmentally friendly fuels. Nevertheless, it is underscored that relying just on economic incentives may not be enough, and more actions are necessary to guarantee the durability of the situation in the long run. This situation highlights the need of a comprehensive plan that include ongoing enhancements and supplementary actions beyond just financial incentives.

In summary, this research offers significant insights into the impacts of several initiatives designed to decrease greenhouse gas (GHG) emissions in the marine industry. The enduring effects of various tactics and policy interventions unequivocally highlight the need for more efficient policies and strategies. Although the existing IMO initiatives demonstrate some advancements, the results indicate the need for more assertive and comprehensive efforts. These findings emphasize the need for more stringent rules, decreases in speed, and the incorporation of economic incentives to accomplish sustainability objectives in the marine industry.

8. Conclusion

This project demonstrates the substantial potential of system dynamics modeling to evaluate the complex and interrelated factors influencing GHG emissions in maritime shipping. By focusing on CO2 emissions as a primary indicator, we have been able to simulate and analyze the impacts of various strategies, including IMO measures, aggressive emission reduction policies, speed adjustments, and economic incentives related to fuel costs.

Our findings highlight several key insights in terms of current IMO strategies, aggressive measures, speed reductions, economic incentives. While these strategies show some initial effectiveness, they are insufficient to significantly curb long-term emissions growth. There is a clear need for more robust and comprehensive policies. Implementing stricter regulations and leveraging advanced technologies can lead to substantial reductions in emissions, demonstrating the importance of bold and decisive action in mitigating environmental impacts. Lowering ship speeds proves to be a straightforward and highly effective measure for reducing CO2 emissions. Both moderate and significant speed reductions present clear benefits over maintaining current speeds. Adjusting the costs of fuels, such as increasing HFO prices and decreasing LNG costs, can drive a significant shift towards cleaner fuels and lower emissions, underscoring the role of market-based strategies in environmental policy.

Despite these valuable insights, it is crucial to acknowledge the limitations of our study. One of the primary limitations of the model is its dependency on certain assumptions and input parameters, particularly concerning fuel prices and the behavioural responses of shipping companies to economic incentives. Fuel prices, for instance, can fluctuate significantly due to geopolitical events, market dynamics, and technological advancements. These fluctuations may impact the outcomes of the scenarios explored, potentially leading to variations in the effectiveness of speed reductions, fuel-switching, and other strategies. The model primarily focuses on container shipping and excludes port-side emissions. However, the model's flexibility allows for adaptation to other ship types by modifying relevant parameters, broadening its applicability across the maritime sector. Moreover, while the model effectively simulates the impacts of various strategies on CO2 emissions for the vessel types included in this study, its applicability to other types of vessels remains to be tested. Different vessel classes, such as bulk carriers, tankers, or passenger ships, may exhibit different operational profiles and responses to regulatory and market-based measures. Therefore, applying this model to a broader range of vessel types would require careful consideration of these differences. The reason of considering CO2 emission from container ships in this project is that according to [74] the proportion of carbon dioxide emissions from container ships has the highest level (22%). Additionally, the model is helpful for maritime stakeholders to know the efficacy of various GHG mitigation strategies. But GHG are produced throughout the whole life cycles not only in cargo transportation but also in fuel production and delivery. Although, stakeholders for fuel production and delivery are important part of maritime sector, IMO’s mitigation strategies are implemented for more stakeholders for cargo transportation. Therefore, the boundary of the developed model is set for cargo transportation. Besides, in terms of economic impact, costs of the alternative fuels are only considered in the model. However, in terms of market sharing, setting facilities and infrastructure, and economic situation in the globe and sector, economic impacts can also be added into the model. The lack of this side of economic impact in the model is one of the limitations of the model. Finally, Fuel consumption is influence by other factors (such as weather, trim, hull condition, etc.). It is an energy efficiency optimization problem onboard ship. These are not part of the current model, but it can be handled in the future studies.

To better understand the robustness of our findings, a comprehensive sensitivity analysis would be valuable. In this project, model validity is tested with real data of some dynamics on a certain time. The model largely focuses on container transportation, aligning with the required mitigation methods in IMO GHG strategy plans, and does not include emissions from ports. This analysis could explore the impact of varying key parameters, such as fuel prices, ship operating speeds, and technological adoption rates, on the overall emissions reductions. For example, by examining a range of fuel price scenarios, we can assess how sensitive our results are to market volatility and determine the conditions under which the model's predictions hold true. This application is implemented by using only one value of the dynamics on the certain time instead of varying the values on the several time. Additionally, sensitivity analysis could help identify which parameters have the most significant influence on the model's outcomes, allowing us to prioritize data collection and model refinement efforts in future work. In addition, more detailed studies can be conducted in future studies on topics such as different ship types, the impact of technological developments, emissions from ports, the roles of port states and flag states in reducing GHG emissions, and the impact of seasonal changes. This would enhance the reliability of the model and ensure that it remains a valuable tool for policymakers and industry stakeholders, even in the face of uncertainty.

As the deliveries of this project, our research has been shared through various prestigious platforms. The interim report of the project is presented at the IAMU-AGA 2023 and the outcomes of the project will be presented in IMLA Conference on 24 September 2024. The abstract and full paper for the IMLA Conference 24 has been already accepted and it will be presented on 24 September 2024. Additionally, it is aimed to submit the project results to a high-index maritime transportation-related journal. These opportunities will enable us to contribute to the global conversation on maritime emissions reduction and foster collaborative efforts towards a more sustainable future.

This study was conducted in accordance with the International Maritime Organization's objective of achieving net zero greenhouse gas emissions. The study's results and the projected greenhouse gas (GHG) emissions align with the International Maritime Organization's (IMO) objectives, indicating compatibility between the two. Hence, the project coincides with IMO's statistics on greenhouse gas (GHG) emissions, and its authenticity has been verified. In addition, the optimum overlap between the base scenario data and historical data specified in Figures 26 and 27 is another factor that shows the validity of the model.

The project team, consisting of Istanbul Technical University Maritime Faculty (Project Coordinator) and Shanghai Maritime University, has conducted extensive research and published several academic publications and studies on greenhouse gas (GHG) emissions in the marine industry. The knowledge acquired from these investigations makes a substantial contribution to the project. By integrating economic incentives with technological advancements and operational improvements, and through continuous collaboration with stakeholders and academic partners like Shanghai Maritime University, we can develop and implement effective strategies that drive substantial and sustained reductions in maritime GHG emissions.

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