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RESEARCH ARTICLE

# Carbon reduction and cost control of container shipping in response to the European Union Emission Trading System

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## Abstract

In response to the EU ETS, we propose a cost model considering carbon emissions for container shipping, calculating fuel consumption, carbon emissions, EUA cost, and total cost of container shipping. We take a container ship operating on a route from the Far East to Northwest Europe as a case study. Environmental and economic impacts of including maritime transport activities in the EU ETS on container shipping are assessed. Results show that carbon emissions from the selected container ship using methanol are the smallest, and total cost of the selected container ship using methanol is the lowest. Among MGO, HFO, LNG, and methanol, methanol is the most environmentally and cost-effective option. Using LNG has greater environmental benefit, while using HFO has greater economic benefit. Compared to MGO, carbon reduction effects of LNG and methanol are 14.2% and 57.1%, and their cost control effects are 7.8% and 26.5%. Compared to HFO, carbon reduction effects of LNG and methanol are 11.7% and 55.8%, and the cost control effect of methanol is 9.3%. Speed reduction is effective in achieving carbon reduction and cost control of container shipping only when the sailing speed of the selected container ship is greater than 8.36 knots. Once the sailing speed is less than this threshold, speed reduction will increase carbon emissions and total cost of container shipping. This model can assess the environmental and economic impacts of including maritime transport activities in the EU ETS on container shipping and explore the measures to achieve carbon reduction and cost control of container shipping in response to the EU ETS.

**Keywords** Container shipping · European Union Emission Trading System (EU ETS) · Carbon reduction · Cost control · Alternative fuels · Speed reduction

## Introduction

Maritime transport is the backbone of international trade (Du et al. 2019; Wu et al. 2021), responsible for over 70% of international trade value and around 90% of international trade volume (Li et al. 2022; Wu et al. 2022). As the main mode of transport, maritime transport is characterized by long sailing distances, large transportation quantities, and low unit costs. Due to the development of the economy and trade around the world, carbon emissions from maritime transport activities are constantly increasing (Wada et al. 2021; You and Lee 2022). According to the Fourth IMO GHG Study (IMO 2020), from 2012 to 2018, carbon emissions from maritime transport increased from 962 million tons to 1056 million tons (Li et al. 2022), and their share rose from 2.76% to 2.89% (Farkas et al. 2022; Ryu et al. 2023). It is expected that without any additional measures, carbon emissions from maritime transport will increase to

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90–130% of 2008 emissions by 2050 (Fricaudet et al. 2023). Therefore, reducing carbon emissions from maritime transport is a matter of urgency.

Container ships are the preferred mode of transport for international trade, as they can carry large quantities of containers more cheaply than other modes of transport (Goicoechea and Abadie 2021). Responsible for over 17% of maritime trade, they are an important part of maritime transport (Kokosalakis et al. 2021). The average service speed of container ships is the highest of all ship types. On one hand, this high-speed tendency makes container shipping more efficient and more profitable with more round-trips. On the other hand, due to high sailing speed, container ships are the largest source of carbon emissions in maritime transport (Shimotsuura et al. 2023). Therefore, more efforts are necessary for carbon reduction of container shipping.

In order to reduce carbon emissions from maritime transport, many initiatives have been taken at a global and regional level. As the main regulatory agency of maritime transport (Joseph et al. 2021), the International Maritime Organization (IMO) strives to reduce carbon emissions from maritime transport (Inal et al. 2022; You et al. 2023). In 2018, IMO adopted the Initial IMO Strategy on Reduction of GHG Emissions from Ships (hereinafter the Initial Strategy), setting out a vision to reduce carbon emissions from maritime transport (IMO 2018a). Levels of ambition directing the Initial Strategy mainly include (IMO 2018b): (1) peaking carbon emissions from maritime transport as soon as possible; (2) reducing the total annual carbon emissions from maritime transport by at least 50% by 2050 compared to 2008; (3) reducing carbon intensity of maritime transport by at least 40% by 2030, and pursuing efforts towards 70% by 2050, compared to 2008 (Abreu et al. 2023). In 2023, IMO revised the Initial Strategy and adopted the 2023 IMO Strategy on Reduction of GHG Emissions from Ships (hereinafter the 2023 IMO GHG Strategy) (IMO 2023b). Levels of ambition directing the 2023 IMO GHG Strategy mainly include (IMO 2023a) (1) peaking carbon emissions from maritime transport as soon as possible; (2) reaching net-zero carbon emissions by or around, i.e., close to, 2050; and (3) reducing carbon intensity of maritime transport by at least 40% by 2030, compared to 2008 (Xu et al. 2024). Comparing the two strategies, it can be found that IMO's carbon reduction ambition is strengthening. This will certainly accelerate the process of carbon reduction of maritime transport.

As a pioneer and leader in reducing carbon emissions and combating climate change, the European Union (EU) has pledged to reduce carbon emissions by at least 55% compared to 1990 levels by 2030 (Watanabe et al. 2022) and achieve climate neutrality by 2050 (Oloruntobi et al. 2024). The EU Emission Trading System (EU ETS) is the key tool for the EU to reduce carbon emissions cost-effectively, and the cornerstone of its policy to combat climate change such as global warming (Mao et al. 2024). In 2005, the EU began to implement the first international ETS (Ding et al. 2020). Since 2012, carbon emissions from aviation have been included in the EU ETS (Christodoulou et al. 2021). On June 22, 2022, the European Parliament voted for an amendment to include maritime transport activities in the EU ETS (Mao et al. 2024). The provisions relating to the inclusion of carbon emissions from maritime transport activities in the EU ETS come into force from January 1, 2024 (EUR-Lex 2023a). It applies to ships of 5000 gross tonnage (GT) and above in respect of carbon emissions emitted during their voyages that transport cargo or passengers for commercial purposes (EUR-Lex 2023b). Shipping companies are required to purchase and surrender allowance costs for EU-related carbon emissions (Sun et al. 2024), which inevitably leads to increased total cost of maritime transport (Zhu et al. 2023).

Under the EU ETS, this paper constructs a cost model considering carbon emissions for container shipping to assess the environmental and economic impacts of including maritime transport activities in the EU ETS on container shipping. A container ship operating on the container shipping route from the Far East to Northwest Europe is taken as a case study. This paper calculates the fuel consumption, carbon emissions, EUA cost, and total cost of the selected container ship. In response to the EU ETS, this paper identifies two potential measures for container shipping to reduce carbon emissions and control total cost and evaluates the effects of the above measures. Faced with the inclusion of maritime transport activities in the EU ETS, this paper aims to solve the three questions: (1) What are the impacts of including maritime transport activities in the EU ETS on container shipping? (2) In response to the EU ETS, what are the measures to reduce carbon emissions from container shipping? What are the effects of carbon reduction measures? (3) In response to the EU ETS, what are the measures to control total cost of container shipping? What are the effects of cost control measures?

This paper contributes to carbon reduction and cost control of container shipping in response to the EU ETS by constructing a cost model considering carbon emissions under the EU ETS. Assessing the environmental and economic impacts of including maritime transport activities in the EU ETS on container shipping is the basis and prerequisite for identifying effective measures in response to the EU ETS for container shipping. This cost model considering carbon emissions can help container ships reduce carbon emissions, control total cost, and enhance sustainability and competitiveness in response to the EU ETS.

The rest of this paper is organized as follows. "Literature review" reviews the relevant literature. The cost model considering carbon emissions is constructed for container shipping in "Method". "Case study" verifies the applicability of the proposed model through case study. The conclusions are provided in "Conclusions".

## Literature review

The topic of including maritime transport in the EU ETS has been extensively studied by scholars. Some scholars pay attention to its history and development. Wettestad and Gulbrandsen (2022) revisited the process of including maritime transport in the EU ETS. Liu et al. (2023) analyzed the evolution of the EU ETS, the main EU shipping emission reduction policy. Christodoulou and Cullinane (2023) explored the historical developments in the implementation of a maritime ETS from IMO discussions and EU processes. After discussing the background and development of the EU ETS, Mao et al. (2024) summarized the purposes of including maritime transport in the EU ETS, mainly including the following objectives: the primary objective is to reduce carbon emissions from maritime transport, the secondary objective is to strengthen the EU's influence in setting rules for reducing carbon emissions from maritime transport, and the important objectives are to maintain the competitiveness of maritime transport and gain economic benefits.

Most scholars focused on its impacts. Hermeling et al. (2015) evaluated the effects of an EU regional maritime ETS and analyzed the environmental, economic, and legal impacts of the EU maritime ETS. Christodoulou et al. (2021) pointed out that the economic impacts on the maritime transport from its inclusion in the EU ETS mainly come from the design elements of the EU ETS, which are the geographical scope, the emission allowance unit price, and the emission allowance allocation method of the EU ETS. Considering the different scenarios formed by the above three elements, the economic impact assessment model is used to assess the direct economic impact on the maritime transport from its inclusion in the EU ETS. A sensitivity analysis is used to demonstrate the impacts of different geographical scope, emission allowance prices, and emission allowance allocation methods of including maritime transport in the EU ETS (independent variables) on the direct costs of the maritime sectors (dependent variables) and how sensitive these costs are to different scenarios. Their results indicated that shipping companies will be directly economically affected by the inclusion of maritime transport in the EU ETS, as their operational costs will increase by the additional allowance costs. They considered the additional allowance costs will incentivize investment in carbon reduction technologies and clean marine fuels only if shipping companies cannot pass on their costs on to the shippers. Cariou et al. (2021) estimated the potential impacts of EU maritime ETS on European oil seaborne trades and evaluated the effectiveness of the EU ETS as a means of promoting innovation in maritime transport. Their findings suggested that EU maritime ETS could help maritime transport reduce carbon emissions and accelerate the decarbonization. Wang et al. (2021) analyzed the impacts of including maritime transport activities in the EU ETS on technology investment, transport mode shift, and liner shipping service design. They proposed applicable ships should pay high carbon emission costs as a result of including maritime transport in the EU ETS, and shipping companies need to balance the tradeoff of annual fixed cost, annual fuel cost, and annual carbon emission cost. The direct consequences of this inclusion may be that shipping companies choose to invest in emission reduction technologies, use clean fuels (e.g., LNG, methanol), and operate ships in more emission reduction ways (e.g., slow steaming). Slow steaming is recognized as an effective short-term operational measure, which can help reduce fuel consumption and consequently reduce carbon emissions by sailing at slow speed. Wang et al. (2015) analyzed the economic impacts of open ETS and maritime only ETS on the shipping sector and concluded that two ETS mechanisms can reduce sailing speed, fuel consumption, and carrier output for both container and dry bulk sectors. Goicoechea and Abadie (2021) proposed the economic optimization model to obtain the optimal slow steaming speed of container ships and analyzed the impacts of the EU ETS on the optimal speed. They focused on container ships as they sail most nautical miles per year and produce the most carbon emissions. Their results showed that the optimal speed decreases as the carbon price increases and/or emission cost percentage increases, and consequently, carbon emissions decrease.

Through the literature review, it can be found that existing literature mainly focused on exploring the environmental and economic impacts of including maritime transport activities in the EU ETS. It is obvious that the inclusion of maritime transport activities will have a direct economic impact on the maritime sectors. Faced with the EU ETS, shipping companies tend to favor two measures, one is the use of alternative fuels represented by LNG and methanol; the other is slow steaming, also known as speed reduction. Therefore, on the basis of assessing the environmental and economic impacts of including maritime transport activities in the EU ETS on container shipping, this paper investigates the measures for container shipping to reduce carbon emissions and control total cost in response to the EU ETS, and how effective these measures are.

## Method

### Problem description

The EU regulation providing for the inclusion of maritime transport activities in the EU ETS has entered into force on June 5, 2023 (EUR-Lex 2023b). The key equipment that provides power for container shipping mainly includes two parts: the main engine and the auxiliary engine. Container shipping is divided into two stages in this paper: the sailing stage and the in-port stage.

Therefore, this paper constructs a cost model considering carbon emissions for container shipping to assess the environmental and economic impacts of including maritime transport activities in the EU ETS. On this basis, this paper explores effective measures for container shipping companies to reduce carbon emissions and control total costs in response to the EU ETS.

## Basic assumptions

The cost model considering carbon emissions constructed in this paper for container shipping is based on the following assumptions.

Assumption 1: According to the so-called cubic law (Meng et al. 2016; Yan et al. 2020), fuel consumption is a cubic function of sailing speed (Fagerholt et al. 2015; Psaraftis and Kontovas 2013; Zhang et al. 2021), and is not related to the type of fuel (Fan et al. 2020).

Assumption 2: The hull of the container ship providing container shipping service is in good condition and suitable for navigation. The container shipping route is fixed. The main engine and auxiliary engine of the container ship use the same type of fuel.

Assumption 3: Container ships only transport dry containers, and reefer containers are not considered (Doudnikoff and Lacoste 2014).

## Parameter setting

The parameters are set in Table 1.

## Mathematical model

### Fuel consumption

The main engine and auxiliary engine are the key equipment to provide power for container shipping. As the main power equipment of container shipping, the main engine converts chemical energy of marine fuels into mechanical energy of container ships to generate propulsive force and propel ships forward. As the auxiliary power equipment of container shipping, the auxiliary engine supports the operation of the main engine and provides auxiliary functions for container ships.

The fuel consumption of the main engine follows the cubic law of sailing speed and design speed (Corbett et al. 2009; Dong and Tae-Woo Lee 2020). According to Cariou and Cheaitou (2012) and Doudnikoff and Lacoste (2014), fuel consumption of the main engine of a container ship can be defined as Eqs. (1)–(2):

$$F^M = SFOC^M EL^M PS^M \left(\frac{v_s}{v_d}\right)^3 \frac{24}{10^6} \tag{1}$$

where $M$ denotes the main engine of a container ship, $F^M$ is the fuel consumption of the main engine of a container ship per day (tons/day), $SFOC^M$ is the specific fuel oil consumption of the main engine of a container ship (g/kWh), $EL^M$ is the main engine load of a container ship (%), $PS^M$ is the main engine power of a container ship (kW), $v_s$ is the sailing speed of a container ship (knots), and $v_d$ is the design speed of a container ship (knots).

$$F_M = F^M \cdot t_S = SFOC^M EL^M PS^M \frac{Dv_s^2}{v_d^3} \frac{1}{10^6} \tag{2}$$

where $F_M$ is the fuel consumption of the main engine of a container ship per round-trip (tons), $D$ is the round-trip distance of a container ship (nautical miles), and $t_S$ is the sailing time of a container ship per round-trip (days). They can be calculated as Eqs. (3)–(4):

$$D = \sum_{i,j\in P} D_{ij} \tag{3}$$

$$t_S = \sum_{i,j\in P} t_{S_{ij}} = \sum_{i,j\in P} \frac{D_{ij}}{24v_s} = \frac{D}{24v_s} \tag{4}$$

where $i$, $j$ denote ports of call of a container ship on a container shipping route, $i,j \in P$, port $j$ is the next port after port $i$ on the route, $D_{ij}$ is the sailing distance of a container ship from port $i$ to port $j$ (nautical miles), and $t_{S_{ij}}$ is the time of a container ship sailing from port $i$ to port $j$ (days), which can be calculated as Eq. (5):

$$t_{S_{ij}} = \frac{D_{ij}}{24v_s} \tag{5}$$

The fuel consumption of the auxiliary engine is not related to the sailing speed (Doudnikoff and Lacoste 2014). According to Cariou and Cheaitou (2012) and Doudnikoff and Lacoste (2014), fuel consumption of the auxiliary engine of a container ship can be defined as Eqs. (6)–(7):

$$F^A = SFOC^A EL^A PS^A \frac{24}{10^6} \tag{6}$$

where $A$ denotes the auxiliary engine of a container ship, $F^A$ is the fuel consumption of the auxiliary engine of a container ship per day (tons/day), $SFOC^A$ is the specific fuel oil consumption of the auxiliary engine of a container ship (g/kWh), $EL^A$ is the auxiliary engine load of a container ship

**Table 1** Parameter setting

| Parameter | Meaning | Unit |
|---|---|---|
| $P$ | Set of all ports of call of a container ship on a container shipping route | / |
| $A$ | Set of all EU ports of call of a container ship on a container shipping route | / |
| $P \backslash A$ | Set of all non-EU ports of call of a container ship on a container shipping route | / |
| $i, j$ | Ports of call of a container ship on a container shipping route, $i, j \in P$, and port $j$ is the next port after port $i$ on a container shipping route | / |
| $k$ | Port of call of a container ship on a container shipping route,$k \in P$ | / |
| $D$ | Round-trip distance of a container ship | Nautical miles |
| $N$ | Round-trip number of a container ship | / |
| $v_d$ | Design speed of a container ship | Knots |
| $v_s$ | Sailing speed of a container ship | Knots |
| $t_{S_{ij}}$ | Time of a container ship sailing from port $i$ to port $j$ | Days |
| $t_S$ | Sailing time of a container ship per round-trip | Days |
| $t_{IP_k}$ | Time of a container ship in port $k$ | Days |
| $t_{IP}$ | In-port time of a container ship per round-trip | Days |
| $t_{total}$ | Round-trip time of a container ship | Days |
| $SFOC^M$ | Specific fuel oil consumption of the main engine of a container ship | g/kWh |
| $SFOC^A$ | Specific fuel oil consumption of the auxiliary engine of a container ship | g/kWh |
| $EL^M$ | Main engine load of a container ship | % |
| $EL^A$ | Auxiliary engine load of a container ship | % |
| $PS^M$ | Main engine power of a container ship | kW |
| $PS^A$ | Auxiliary engine power of a container ship | kW |
| $F$ | Fuel consumption of a container ship | Tons |
| $F^M$ | Fuel consumption of the main engine of a container ship per day | Tons/day |
| $F^A$ | Fuel consumption of the auxiliary engine of a container ship per day | Tons/day |
| $F_M$ | Fuel consumption of the main engine of a container ship per round-trip | Tons |
| $F_A$ | Fuel consumption of the auxiliary engine of a container ship per round-trip | Tons |
| $F_{S_{ij}}$ | Fuel consumption of a container ship sailing from port $i$ to port $j$ | Tons |
| $F_S$ | Fuel consumption of a container ship during the sailing stage per round-trip | Tons |
| $F_{IP_k}$ | Fuel consumption of a container ship in port $k$ | Tons |
| $F_{IP}$ | Fuel consumption of a container ship during the in-port stage per round-trip | Tons |
| $F_{total}$ | Total fuel consumption of a container ship per round-trip | Tons |
| $C_F$ | Conversion factor between fuel consumption and carbon emissions of a type of fuel | $t$CO$_2$/$t$Fuel |
| $E$ | Carbon emissions from a container ship | $t$CO$_2$ |
| $E_M$ | Carbon emissions from the main engine of a container ship per round-trip | $t$CO$_2$ |
| $E_A$ | Carbon emissions from the auxiliary engine of a container ship per round-trip | $t$CO$_2$ |
| $E_{S_{ij}}$ | Carbon emissions of a container ship sailing from port $i$ to port $j$ | $t$CO$_2$ |
| $E_S$ | Carbon emissions from a container ship during the sailing stage per round-trip | $t$CO$_2$ |
| $E_{IP_k}$ | Carbon emissions from a container ship in port $k$ | $t$CO$_2$ |
| $E_{IP}$ | Carbon emissions from a container ship during the in-port stage per round-trip | $t$CO$_2$ |
| $E_{total}$ | Total carbon emissions from a container ship per round-trip | $t$CO$_2$ |
| $E_S^{EU}$ | EU-related carbon emissions from a container ship during the sailing stage per round-trip | $t$CO$_2$ |
| $E_{ij}^{EU}$ | Calculated EU-related carbon emissions of a container ship sailing from port $i$ to port $j$ | $t$CO$_2$ |
| $E_{IP}^{EU}$ | EU-related carbon emissions from a container ship during the in-port stage per round-trip | $t$CO$_2$ |
| $E_k^{EU}$ | Calculated EU-related carbon emissions from a container ship in port $k$ | $t$CO$_2$ |
| $E^{EU}$ | EU-related carbon emissions from a container ship per round-trip | $t$CO$_2$ |
| $P_{EUA}$ | EUA price per carbon emission | USD/tCO$_2$ |
| $C_{fuel}$ | Fuel price | USD/$t$Fuel |
| $C_f$ | Fixed cost of a container ship per day (including capital cost, crew wage, insurance premium, repair and maintenance cost, storage and lubrication cost and administration cost) | USD/day |
| $C_{EUA}$ | EUA cost of a container ship per round-trip | USD |
| $C_{total}$ | Total cost of a container ship per year | USD |

(%), and $PS^A$ is the auxiliary engine power of a container ship (kW).

$$F_A = F^A \cdot t_{total} = SFOC^A EL^A PS^A \left( \frac{D}{24v_s} + t_{IP} \right) \frac{24}{10^6} \tag{7}$$

where $F_A$ is the fuel consumption of the auxiliary engine of a container ship per round-trip (tons), and $t_{total}$ is the round-trip time of a container ship (days), which consists of the sailing time and in-port time (Wang and Meng 2012). It can be calculated as Eq. (8):

$$t_{total} = t_S + t_{IP} = \frac{D}{24v_s} + t_{IP} \tag{8}$$

where $t_{IP}$ is the in-port time of a container ship (days), which includes manoeuvring and berthing time (Jiang et al. 2014). It can be calculated as Eq. (9):

$$t_{IP} = \sum_{k \in P} t_{IP_k} \tag{9}$$

where $k$ denotes a port of call of a container ship on a container shipping route, $k \in P$, and $t_{IP_k}$ is the time of a container ship in port $k$ (days).

The sailing stage and in-port stage are the main stages of container shipping.

During the sailing stage, the main engine and auxiliary engine operate simultaneously (Jeong et al. 2018). Fuel consumption during the sailing stage of container shipping can be defined as Eqs. (10)–(11) (Corbett et al. 2009):

$$\begin{aligned} F_{S_{ij}} &= (F^M + F^A) t_{S_{ij}} \\ &= (SFOC^M EL^M PS^M \frac{D_{ij} v_s^2}{v_d^3} + SFOC^A EL^A PS^A \frac{D_{ij}}{v_s}) \frac{1}{10^6} \end{aligned} \tag{10}$$

where $F_{S_{ij}}$ is the fuel consumption of a container ship sailing from port $i$ to port $j$ (tons).

$$\begin{aligned} F_S &= \sum_{i,j \in P} F_{S_{ij}} = \sum_{i,j \in P} (SFOC^M EL^M PS^M \frac{D_{ij} v_s^2}{v_d^3} + SFOC^A EL^A PS^A \frac{D_{ij}}{v_s}) \frac{1}{10^6} \\ &= (SFOC^M EL^M PS^M \frac{D v_s^2}{v_d^3} + SFOC^A EL^A PS^A \frac{D}{v_s}) \frac{1}{10^6} = (F^M + F^A) t_S \end{aligned} \tag{11}$$

where $F_S$ is the fuel consumption of a container ship during the sailing stage per round-trip (tons).

During the in-port stage, the main engine stops working, while the auxiliary engine continues to work (Doudnikoff and Lacoste 2014). Fuel consumption during the in-port stage of container shipping can be defined as Eqs. (12)–(13) (Psaraftis and Kontovas 2014):

$$F_{IP_k} = F^A \cdot t_{IP_k} = SFOC^A EL^A PS^A t_{IP_k} \frac{24}{10^6} \tag{12}$$

where $F_{IP_k}$ is the fuel consumption of a container ship in port $k$ (tons).

$$\begin{aligned} F_{IP} &= \sum_{k \in P} F_{IP_k} = \sum_{k \in P} SFOC^A EL^A PS^A t_{IP_k} \frac{24}{10^6} \\ &= SFOC^A EL^A PS^A t_{IP} \frac{24}{10^6} = F^A \cdot t_{IP} \end{aligned} \tag{13}$$

where $F_{IP}$ is the fuel consumption of a container ship during the in-port stage per round-trip (tons).

The total fuel consumption of container shipping is the sum of fuel consumption of the main engine and auxiliary engine of a container ship (Abreu et al. 2023; Corbett et al. 2009). It can be expressed as Eq. (14):

$$\begin{aligned} F_{total} &= F_M + F_A = SFOC^M EL^M PS^M \frac{D v_s^2}{v_d^3} \frac{1}{10^6} \\ &+ SFOC^A EL^A PS^A \left( \frac{D}{24v_s} + t_{IP} \right) \frac{24}{10^6} \end{aligned} \tag{14}$$

where $F_{total}$ is the total fuel consumption of a container ship per round-trip (tons).

As maritime transport is classified into the sailing stage and in-port stage, total fuel consumption of container shipping can also be expressed as Eq. (15):

$$\begin{aligned} F_{total} &= F_S + F_{IP} = SFOC^M EL^M PS^M \frac{D v_s^2}{v_d^3} \frac{1}{10^6} \\ &+ SFOC^A EL^A PS^A \left( \frac{D}{24v_s} + t_{IP} \right) \frac{24}{10^6} \end{aligned} \tag{15}$$

## Carbon emissions

Carbon emissions are directly proportional to fuel consumption (Psaraftis and Kontovas 2013; Zhang et al. 2021). Carbon emissions from container shipping can be defined as Eq. (16) (Bilgili 2021; Fan et al. 2023):

$$E = F \cdot C_F \tag{16}$$

where $E$ is the carbon emissions from a container ship ($t\mathrm{CO}_2$), $F$ is the fuel consumption of a container ship (tons), and $C_F$ is the conversion factor between fuel consumption and carbon emissions ($t\mathrm{CO}_2/t\mathrm{Fuel}$).

Carbon emissions from the main engine of a container ship are illustrated as Eq. (17) (Doudnikoff and Lacoste 2014; Zou and Yang 2023):

$$E_M = F_M \cdot C_F = SFOC^M EL^M PS^M \frac{Dv_s^2}{v_d^3} \frac{C_F}{10^6} \tag{17}$$

where $E_M$ is the carbon emissions from the main engine of a container ship per round-trip ($t\mathrm{CO}_2$).

Carbon emissions from the auxiliary engine of a container ship are illustrated as Eq. (18) (Doudnikoff and Lacoste 2014; Zou and Yang 2023):

$$E_A = F_A \cdot C_F = SFOC^A EL^A PS^A \left( \frac{D}{24v_s} + t_{IP} \right) \frac{24C_F}{10^6} \tag{18}$$

where $E_A$ is the carbon emissions from the auxiliary engine of a container ship per round-trip ($\mathrm{tCO}_2$).

Carbon emissions from the sailing stage of container shipping are derived as Eqs. (19)–(20) (Corbett et al. 2009).

$$E_{S_{ij}} = F_{S_{ij}} \cdot C_F = \left( SFOC^M EL^M PS^M \frac{D_{ij} v_s^2}{v_d^3} + SFOC^A EL^A PS^A \frac{D_{ij}}{v_s} \right) \frac{C_F}{10^6} \tag{19}$$

where $E_{S_{ij}}$ is the carbon emissions of a container ship sailing from port $i$ to port $j$ ($t\mathrm{CO}_2$).

$$\begin{aligned} E_S &= \sum_{i,j \in P} E_{S_{ij}} = \sum_{i,j \in P} \left( SFOC^M EL^M PS^M \frac{D_{ij} v_s^2}{v_d^3} + SFOC^A EL^A PS^A \frac{D_{ij}}{v_s} \right) \frac{C_F}{10^6} \\ &= \left( SFOC^M EL^M PS^M \frac{D v_s^2}{v_d^3} + SFOC^A EL^A PS^A \frac{D}{v_s} \right) \frac{C_F}{10^6} = F_S \cdot C_F \end{aligned} \tag{20}$$

where $E_S$ is the carbon emissions from a container ship during the sailing stage per round-trip ($t\mathrm{CO}_2$).

Carbon emissions from the in-port stage of container shipping are derived as Eqs. (21)–(22):

$$E_{IP_k} = F_{IP_k} \cdot C_F = SFOC^A EL^A PS^A t_{IP_k} \frac{24C_F}{10^6} \tag{21}$$

where $E_{IP_k}$ is the carbon emissions from a container ship in port $k$ ($t\mathrm{CO}_2$).

$$\begin{aligned} E_{IP} &= \sum_{k \in P} E_{IP_k} = \sum_{k \in P} SFOC^A EL^A PS^A t_{IP_k} \frac{24C_F}{10^6} \\ &= SFOC^A EL^A PS^A t_{IP} \frac{24C_F}{10^6} = F_{IP} \cdot C_F \end{aligned} \tag{22}$$

where $E_{IP}$ is the carbon emission from a container ship during the in-port stage per round-trip ($t\mathrm{CO}_2$).

Total carbon emissions from container shipping can be expressed as Eq. (23) (Cariou and Cheaitou 2012; Doudnikoff and Lacoste 2014).

$$\begin{aligned} E_{total} &= F_{total} \cdot C_F = E_M + E_A = (F_M + F_A)C_F = E_S + E_{IP} = (F_S + F_{IP})C_F \\ &= SFOC^M EL^M PS^M \frac{Dv_s^2}{v_d^3} \frac{C_F}{10^6} + SFOC^A EL^A PS^A t_{total} \frac{24C_F}{10^6} \end{aligned} \tag{23}$$

where $E_{total}$ is the total carbon emissions from a container ship per round-trip ($t\mathrm{CO}_2$).

### EUA cost

Under the EU ETS, container shipping companies should surrender allowance cost for EU-related carbon emissions, that is, the EUA cost is incurred. It can be defined as Eq. (24):

$$C_{EUA} = P_{EUA} \cdot \alpha \cdot E^{EU} = \alpha P_{EUA} E^{EU} \tag{24}$$

where $C_{EUA}$ is the EUA cost of a container ship per round-trip (USD), $P_{EUA}$ is the EUA price per carbon emission ($\mathrm{USD}/t\mathrm{CO}_2$), $\alpha$ is the proportion of carbon emissions from maritime transport activities included in the EU ETS every year during an initial phase-in period (%), and $E^{EU}$ is the EU-related carbon emissions from a container ship per round-trip ($t\mathrm{CO}_2$), which can be derived as Eq. (25)–(29):

$$E^{EU} = E_S^{EU} + E_{IP}^{EU} \tag{25}$$

where $E_S^{EU}$ is the EU-related carbon emissions from a container ship during the sailing stage per round-trip ($t$CO$_2$), and $E_{IP}^{EU}$ is the EU-related carbon emissions from a container ship during the in-port stage per round-trip ($t$CO$_2$).

EU-related carbon emissions from a container ship during the sailing stage per round-trip can be obtained as Eqs. (26)–(27):

$$E_S^{EU} = \sum_{i,j \in P} E_{ij}^{EU} \tag{26}$$

where $E_{ij}^{EU}$ is the calculated EU-related carbon emissions of a container ship sailing from port $i$ to port $j$ ($t$CO$_2$). According to the EU directive (EUR-lex 2023a), it can be obtained as Eq. (27):

$$E_{ij}^{EU} = \begin{cases} 50\% \cdot E_{S_{ij}} & i \in A, j \in P \backslash A \\ 50\% \cdot E_{S_{ij}} & i \in P \backslash A, j \in A \\ 100\% \cdot E_{S_{ij}} & i,j \in A \\ 0 \cdot E_{S_{ij}} & i,j \in P \backslash A \end{cases} \tag{27}$$

where $E_{S_{ij}}$ is the actual carbon emissions of a container ship sailing from port $i$ to port $j$ ($t$CO$_2$), which can be calculated as Eq. (19); $P$ denotes the set of all ports of call of a container ship on a container shipping route, $A$ denotes the set of all EU ports of call of a container ship on a container shipping route, $P \backslash A$ denotes the set of all non-EU ports of call of a container ship on a container shipping route, $i$, $j$ denote ports of call of a container ship on a container shipping route, $i,j \in P$, and port $j$ is the next port after port $i$ on the container shipping route. They can be stated as a pair of port $(i,j)$.

EU-related carbon emissions from a container ship during the in-port stage per round-trip can be obtained as Eqs. (28)–(29):

$$E_{IP}^{EU} = \sum_{k \in P} E_k^{EU} \tag{28}$$

where $E_k^{EU}$ is the calculated EU-related carbon emission from a container ship in port $k$ ($t$CO$_2$). According to the EU directive (EUR-lex 2023a), it can be obtained as Eq. (29):

$$E_k^{EU} = \begin{cases} 100\% \cdot E_{IP_k} & k \in A \\ 0 \cdot E_{IP_k} & k \in P \backslash A \end{cases} \tag{29}$$

where $E_{IP_k}$ is the actual carbon emissions from a container ship in port $k$ ($t$CO$_2$), which can be calculated as Eq. (21).

### Total cost

The total cost of container shipping can be divided into two parts: fixed cost and variable cost (Goicoechea and Abadie 2021). Fixed cost mainly includes capital cost, crew wage, insurance premium, repair and maintenance cost, storage and lubrication cost, and administration cost. Under the EU ETS, variable cost mainly includes fuel cost and EUA cost.

Total cost of container shipping can be expressed as Eq. (30):

$$\begin{aligned} C_{total} &= C_f \cdot t_{year} + F_{total} \cdot C_{fuel} \cdot N + C_{EUA} \cdot N \\ &= C_f \cdot t_{year} + \left( SFOC^M EL^M PS^M \frac{Dv_s^2}{v_d^3} + SFOC^A EL^A PS^A \left( \frac{D}{v_s} + t_{IP} \right) \right) \frac{C_{fuel}}{10^6} \cdot N \\ &+ \alpha P_{EUA} \cdot \left( \sum\nolimits_{i,j \in P} E_{ij}^{EU} + \sum\nolimits_{k \in P} E_k^{EU} \right) \cdot N \end{aligned} \tag{30}$$

where $C_{total}$ is the total cost of a container ship per year (USD), $C_f$ is the fixed cost of a container ship per day (USD/day), $t_{year}$ is the number of days in a year (days), $C_{fuel}$ is the fuel price (USD/$t$Fuel), and $N$ is the round-trip number of a container ship per year.

## Case study

In order to verify the applicability of the proposed cost model considering carbon emissions for container shipping, this paper selects a container ship on the container shipping route from Far East to Northwest Europe as a case study.

### Ship and route selection

The information of the selected container ship and container shipping route is summarized in Table 2. According to the EU directive (EUR-Lex 2023a), the proportions of carbon emissions from maritime transport activities included in the EU ETS from 2025 to 2027 during an initial phase-in period are listed in Table 3. Tables 4 and 5 present the sailing time and in-port time of the selected container ship on the container shipping route.

**Table 2** Selected container ship, container shipping route, and related cost information

| Ship, route and cost information | Value |
|---|---|
| Selected container ship capacity (TEU)[a] | 20,119 |
| Specific fuel oil consumption of the main engine (g/kWh)[b] | 206 |
| Main engine load of the selected container ship (%)[c] | 80 |
| Main engine power of the selected container ship (kW)[d] | 55,000 |
| Design speed of the selected container ship (knots)[a] | 22.6 |
| Specific fuel oil consumption of the auxiliary engine (g/kWh)[b] | 221 |
| Auxiliary engine load of the selected container ship (%)[c] | 50 |
| Auxiliary engine power of the selected container ship (kW)[d] | 8289 |
| Round-trip distance of the selected container ship (nautical miles)[e] | 23,677.05 |
| Round-trip time of the selected container ship (days)[f] | 80.82 |
| Round-trip number of the selected container ship[g] | 4 |
| Capital cost (USD/day)[g] | 48,076 |
| Crew wage (USD/day)[g] | 5807 |
| Insurance premium (USD/day)[g] | 2978 |
| Repair and maintenance cost (USD/day)[g] | 8016 |
| Storage and lubrication cost (USD/day)[g] | 6575 |
| Administration cost (USD/day)[g] | 1230 |
| Fixed cost (USD/day)[g] | 72,682 |
| EUA price (USD/$t$CO$_2$)[h] | 97.2 |
| Price of marine gas oil (MGO) (USD/$t$)[d] | 883.1 |
| Price of heavy fuel oil (HFO) (USD/$t$)[d] | 493.7 |
| Price of liquefied natural gas (LNG) (USD/$t$)[d] | 743.7 |
| Price of methanol (USD/$t$)[i] | 421.0 |

[a] From COSCO Shipping Lines (2023)

[b] From Wang et al. (2007)

[c] From Corbett et al. (2009) and Cariou and Cheaitou (2012)

[d] From Shipping Intelligence Network (Clarksons 2023)

[e] From Vessel Value Visualization (2023)

[f] From Freightower (2023)

[g] From Doudnikoff and Lacoste (2014) and Fan et al. (2020)

[h] From EMBER (2023)

[i] From Methanex (2024)

**Table 3** Proportions of carbon emissions from maritime transport activities included in the EU ETS from 2025 to 2027

| Year | Proportions of carbon emissions from maritime transport activities included in the EU ETS |
|---|---|
| 2025 | 40% of verified carbon emissions reported for 2024 |
| 2026 | 70% of verified carbon emissions reported for 2025 |
| 2027 | 100% of verified carbon emissions reported for 2026 |

Source: EU directive (EUR-lex 2023a) and European Commission (2023)

## Fuel selection

Marine gas oil (MGO) and heavy fuel oil (HFO) are the conventional and prevalent fuels for maritime transport, meeting about 95% of fuel demand of maritime transport in 2018 (Müller-Casseres et al. 2021). Among them, MGO is the fossil fuel with the highest carbon content, accounting for 16% of fuel consumed by maritime transport in 2018 (Tomos et al. 2024). HFO is the most commonly used marine fuel (Ančić et al. 2020). In 2018, HFO provides 79% of fuels for maritime transport (Judith and Jason 2022) and generates nearly 80% of fuel consumption (IMO 2020).

The shift from fossil fuels to alternative fuels has become an inevitable trend in the use of marine fuels. Although conventional fuels will continue to play a role in the future, it is undeniable that the proportion of alternative fuels used as marine fuels is increasing (Hua et al. 2023). Yan et al. (2023) proposed using alternative fuels (low-carbon and zero-carbon fuels) is the consensus to reduce carbon emissions from maritime transport. Referring to their conclusions, LNG and methanol are suitable choices at present. Low-carbon fuels such as LNG and

**Table 4** Sailing time of the selected container ship

| Sailing leg | Departure time | Arrival time | Sailing time (days) |
|---|---|---|---|
| Tianjin-Dalian | 2023 Aug. 12 13:46 | 2023 Aug. 13 8:57 | 0.799 |
| Dalian-Qingdao | 2023 Aug. 14 19:19 | 2023 Aug. 15 17:44 | 0.934 |
| Qingdao-Shanghai | 2023 Aug. 16 16:23 | 2023 Aug. 19 1:34 | 2.383 |
| Shanghai-Ningbo | 2023 Aug. 20 4:14 | 2023 Aug. 20 21:55 | 0.737 |
| Ningbo-Singapore | 2023 Aug. 22 5:37 | 2023 Aug. 27 10:02 | 5.184 |
| Singapore-Piraeus | 2023 Aug. 27 23:11 | 2023 Sep. 11 11:04 | 14.495 |
| Piraeus-Rotterdam | 2023 Sep. 14 8:50 | 2023 Sep. 20 16:50 | 6.333 |
| Rotterdam-Hamburg | 2023 Sep. 23 8:25 | 2023 Sep. 24 14:40 | 1.260 |
| Hamburg-Antwerp | 2023 Sep. 27 2:20 | 2023 Sep. 29 23:25 | 2.878 |
| Antwerp-Shanghai | 2023 Oct. 1 20:45 | 2023 Oct. 27 9:59 | 25.551 |
| Shanghai-Tianjin | 2023 Oct. 29 4:15 | 2023 Oct. 31 6:31 | 2.094 |
| Total sailing time | — | — | 62.65 |

**Table 5** In-port time of the selected container ship

| Port of call | Arrival time | Departure time | In-port time (days) |
|---|---|---|---|
| Tianjin | 2023 Aug. 11 10:53 | 2023 Aug. 12 13:46 | 1.120 |
| Dalian | 2023 Aug. 13 8:57 | 2023 Aug. 14 19:19 | 1.432 |
| Qingdao | 2023 Aug. 15 17:44 | 2023 Aug. 16 16:23 | 0.944 |
| Shanghai | 2023 Aug. 19 1:34 | 2023 Aug. 20 4:14 | 1.111 |
| Ningbo | 2023 Aug. 20 21:55 | 2023 Aug. 22 5:37 | 1.321 |
| Singapore | 2023 Aug. 27 10:02 | 2023 Aug. 27 23:11 | 0.548 |
| Piraeus | 2023 Sep. 11 11:04 | 2023 Sep. 14 8:50 | 2.907 |
| Rotterdam | 2023 Sep. 20 16:50 | 2023 Sep. 23 8:25 | 2.649 |
| Hamburg | 2023 Sep. 24 14:40 | 2023 Sep. 27 2:20 | 2.486 |
| Antwerp | 2023 Sep. 29 23:25 | 2023 Oct. 1 20:45 | 1.889 |
| Shanghai | 2023 Oct. 27 9:59 | 2023 Oct. 29 4:15 | 1.761 |
| Total in-port time | — | — | 18.17 |

methanol can reduce carbon emissions due to their relatively lower carbon content (Stec et al. 2021). LNG is considered to be the alternative fuel with the most potential for maritime transport (Law et al. 2022). It can reduce carbon emissions by at least 20% and virtually eliminates air pollutants compared to conventional marine fuels (Xu and Yang 2020). However, using LNG requires attention to the issue of methane slip (Daniel et al. 2022). At present, methanol as an alternative fuel has been selected and applied to container ships by some shipping companies such as A.P. Moller-Maersk, Ocean Network Express (ONE). LNG and methanol are a short-term solution, but not sufficient to achieve decarbonization of maritime transport.

**Table 6** The carbon content and conversion factor of four types of fuels

| Type of fuel | Carbon content | Conversion factor $C_F$ (tCO$_2$/tFuel) |
|---|---|---|
| Marine gas oil (MGO)[a] | 0.8744 | 3.206 |
| Heavy fuel oil (HFO)[b] | 0.8493 | 3.114 |
| Liquefied natural gas (LNG)[c] | 0.7500 | 2.750 |
| Methanol[c] | 0.3750 | 1.375 |

[a] From ISO 8217 Grades DMX through DMB

[b] From ISO 8217 Grades RME through RMK

[c] From IMO (2018c) and Kim et al. (2023)

This paper selects the above marine fuels for research: fossil fuels (MGO, HFO) and alternative fuels (LNG, methanol). Table 6 gives the carbon content and conversion factor of these fuels.

## Results

### Fuel consumption and carbon emissions of the selected container ship

Figures 1 and 2 present the fuel consumption and carbon emissions of two power equipment of the selected container ship and two main stages of container shipping. It can be found that the sum of the fuel consumption of the main engine and auxiliary engine of the selected container ship is equal to the sum of the fuel consumption of the selected container ship during the sailing stage and in-port stage. Carbon emissions have a similar result, the sum of carbon emissions from two power equipment of

**Fig. 1** Fuel consumption of the selected container ship (tons). **a** Fuel consumption of the main engine and auxiliary engine of the selected container ship. **b** Fuel consumption of the selected container ship during the sailing stage and in-port stage

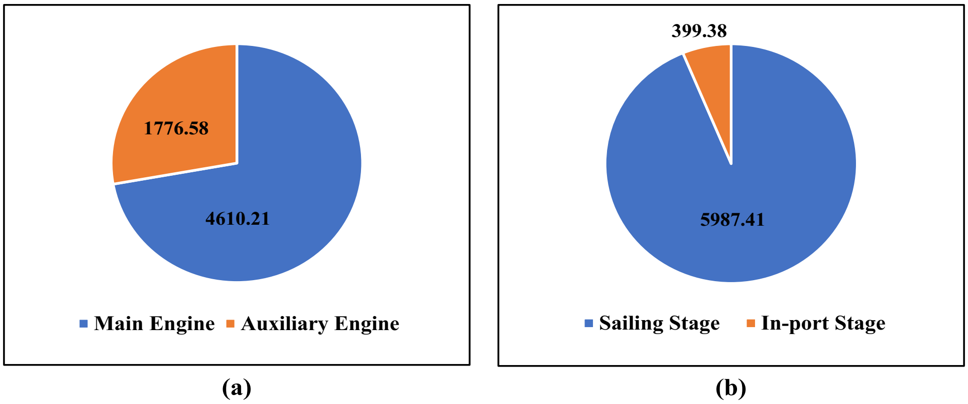

**Fig. 2** Carbon emissions from the selected container ship using MGO and HFO ($t\mathrm{CO}_2$). **a** Carbon emissions from the main engine and auxiliary engine of the selected container ship using MGO. **b** Carbon emissions from the selected container ship using MGO during the sailing stage and in-port stage. **c** Carbon emissions from the main engine and auxiliary engine of the selected container ship using HFO. **d** Carbon emissions from the selected container ship using HFO during the sailing stage and in-port stage

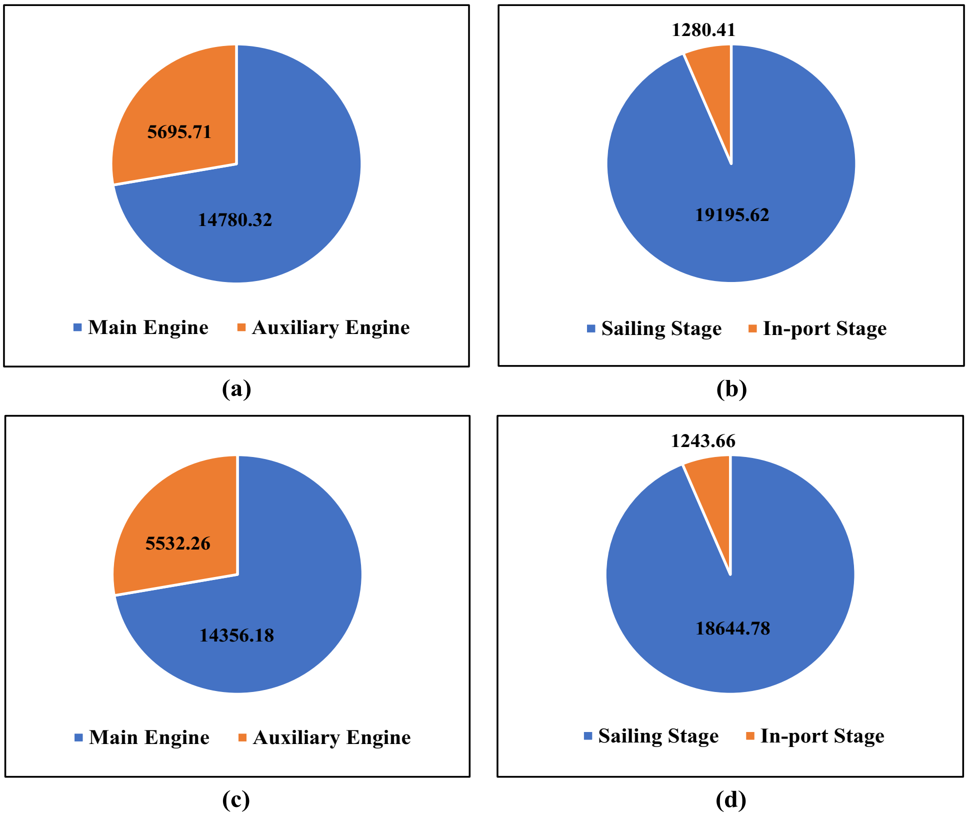

**Table 7** EUA cost and total cost of the selected container ship using MGO and HFO from 2025 to 2027

| Year | Type of fuel | EUA cost (USD) | Total cost (USD) | EUA cost/total cost |
|---|---|---|---|---|
| 2025 | MGO | 1,561,975.08 | 50,651,579.43 | 3.08% |
| | HFO | 1,517,152.34 | 40,658,702.57 | 3.73% |
| 2026 | MGO | 2,733,456.39 | 51,823,060.75 | 5.27% |
| | HFO | 2,655,016.60 | 41,796,566.83 | 6.35% |
| 2027 | MGO | 3,904,937.71 | 52,994,542.06 | 7.37% |
| | HFO | 3,792,880.85 | 42,934,431.09 | 8.83% |

the selected container ship is equal to the sum of carbon emissions from two main stages of container shipping.

## EUA cost and total cost of the selected container ship

For the selected container ship, its total cost consists of fixed cost, fuel cost, and EUA cost. Among them, the fixed cost is a constant; the fuel cost and EUA cost are not only related to the type of fuel used by the selected container ship, but also related to the proportion of carbon emissions from maritime transport activities included in the EU ETS every

**Table 8** Carbon emissions from the selected container ship using four types of fuel

| Carbon emissions ($t\text{CO}_2$) | | MGO | HFO | LNG | Methanol |
|---|---|---|---|---|---|
| Power equipment | Main engine | 14,780.32 | 14,356.18 | 12,678.07 | 6339.03 |
| | Auxiliary engine | 5695.71 | 5532.26 | 4885.59 | 2442.79 |
| Main stage | Sailing stage | 19,195.62 | 18,644.78 | 16,465.37 | 8232.68 |
| | In-port stage | 1280.41 | 1243.66 | 1098.29 | 549.14 |
| Total | | 20,476.03 | 19,888.44 | 17,563.65 | 8781.83 |

year during an initial phase-in period (European Commission 2023).

According to the EU regulation (EUR-Lex 2023b), the EU directive (EUR-Lex 2023a), and the cost model proposed in this paper, the EUA cost and total cost of the selected container ship using MGO and HFO from 2025 to 2027 are shown as Table 7. In terms of fossil fuels, the EUA cost and total cost of the selected container ship using HFO are smaller than that of using MGO. Therefore, it is more economical for the selected container ship to use HFO than to use MGO.

It is clear that including maritime emissions in the EU ETS increases the total cost of container shipping. For the selected container ship using MGO, from 2025 to 2027, its EUA cost is about 3–7% of its total cost, and its total cost increases by about 3–8% due to the EUA cost. For the selected container ship using HFO, from 2025 to 2027, its EUA cost is around 4–9% of its total cost, and its total cost increases by around 4–10% from 2025 to 2027 due to the EUA cost.

## Carbon reduction of container shipping in response to the EU ETS

### Scenario 1: Using alternative fuels

Carbon emissions from two power equipment of the selected container ship, carbon emissions from two main stages of container shipping, and total carbon emissions from the selected container ship using LNG and methanol are shown in Table 8. Comparing the carbon emissions from the selected container ship using four types of fuel, the order from most to least is MGO, HFO, LNG, and methanol. Among the four types of fuel, using methanol is the most environmentally effective for the selected container ship operating on the selected container shipping route. It can be proven that using alternative fuels can indeed reduce carbon emissions from the selected container ship. Compared to MGO, the carbon reduction effects of LNG and methanol are 14.2% and 57.1%. Compared to HFO, their carbon reduction effects are 11.7% and 55.8%. Theoretically, methanol has a better carbon reduction effect than LNG.

### Scenario 2: Speed reduction

As sailing speed has a cubic relationship with carbon emissions from container ships, a small change in sailing speed can have a considerable impact on the carbon emissions from container ships (Dalheim and Steen 2021). Speed reduction does not require major modifications to the ships (Fan et al. 2022), and can be implemented quickly without affecting the ship operation (Bassam et al. 2023).

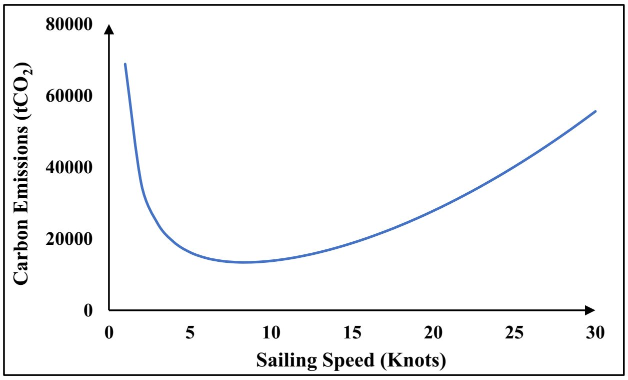

**Fig. 3** Effect of sailing speed on carbon emissions from the selected container ship

**Table 9** Carbon reduction effects of speed reduction on the selected container ship

| Sailing speed before speed reduction (knots) | Percent of speed reduction | | | |
|---|---|---|---|---|
| | 10% | 20% | 30% | 40% |
| 15.75 | 11.32% | 20.60% | 27.57% | 31.82% |
| 20 | 14.49% | 26.97% | 37.31% | 45.25% |

There is a U-shaped relationship between sailing speed and carbon emissions of the selected container ship, as shown in Fig. 3. The lowest point of this U-shaped curve corresponds to the sailing speed of 8.36 knots. When the sailing speed is 8.36 knots, the carbon emissions from the selected container ship using MGO and HFO are 13,762.87 $t\text{CO}_2$ and 13,367.93 $t\text{CO}_2$. When the sailing speed of the selected container ship is greater than 8.36 knots, speed reduction is effective in carbon reduction of container shipping; when the sailing speed of the selected container ship is less than 8.36 knots, speed reduction is ineffective and increases its carbon emissions instead. As the average speed of the selected container ship is 15.75 knots (greater than 8.36 knots), speed reduction is effective at this time.

**Table 10** EUA cost and total cost of the selected container ship using LNG and methanol from 2025 to 2027

| Year | Type of fuel | EUA cost (USD) | Total cost (USD) | EUA cost/total cost |
|---|---|---|---|---|
| 2025 | LNG | 1,339,810.19 | 46,868,144.01 | 2.86% |
| | Methanol | 669,905.10 | 37,954,178.66 | 1.77% |
| 2026 | LNG | 2,344,667.84 | 47,873,001.66 | 4.90% |
| | Methanol | 1,172,333.92 | 38,456,607.48 | 3.05% |
| 2027 | LNG | 3,349,525.48 | 48,877,859.30 | 6.85% |
| | Methanol | 1,674,762.74 | 38,959,036.31 | 4.30% |

Reducing sailing speed of the selected container ship from 15.75 knots (average speed) and 20 knots respectively, the carbon reduction effects of speed reduction are presented in Table 9. It can be seen that when the sailing speed of the selected container ship is reduced by the same percent, the greater the sailing speed before speed reduction, the better the carbon reduction effects of speed reduction.

## Cost control of container shipping in response to the EU ETS

### Scenario 1: Using alternative fuels

Substituting the relevant data of alternative fuels (LNG, methanol) into the constructed cost model, the EUA cost and total cost of alternative fuels are obtained in Table 10. In terms of alternative fuels, the EUA cost and total cost of the selected container ship using methanol are smaller than that of using LNG. Therefore, it is more economical for the selected container ship to use methanol than to use LNG.

The total cost composition of the selected container ship using four types of fuel is presented in Fig. 4. From the point of view of cost composition, for the selected container ship operating on the selected container shipping route, the fixed cost accounts for the largest share of the total cost, the fuel cost is the second largest, and the EUA cost accounts for the smallest share.

Regarding the EUA cost, using LNG and methanol can control the EUA cost of the selected container ship. Notably, using methanol can significantly control the EUA cost of the selected container ship, and consequently control the total cost of the selected container ship. It can be found that the EUA cost of the selected container ship using methanol is only 40–50% of the EUA cost of the selected container ship using the other three types of fuel.

Regarding the total cost, the total cost of the selected container ship using MGO is the largest, and the total cost of the selected container ship using methanol is the smallest. Among the four types of fuel, using methanol is the most cost-effective for the selected container ship operating on the selected container shipping route. Compared to MGO, the cost control effects of LNG and methanol are 7.8% and 26.5%. Compared to HFO, LNG does not currently achieve cost control of container shipping, and the cost control effect of methanol is 9.3%. However, as the technology related to alternative fuels becomes more and more mature, the cost of using LNG and methanol will also be controlled.

Combining the environmental and economic benefits of the four types of fuel selected in the paper, for the selected container ship, using methanol is the most environmentally and cost-effective option, which can effectively realize carbon reduction and cost control of container shipping. The selected container ship using MGO will generate the most carbon emissions and pay the most total cost. The environmental and economic benefits of using HFO and LNG are between those of methanol and MGO. The selected container ship has greater environmental benefit using LNG and greater economic benefit using HFO. Which one should be chosen depends on whether container shipping companies pay more attention to environmental benefit or economic benefit.

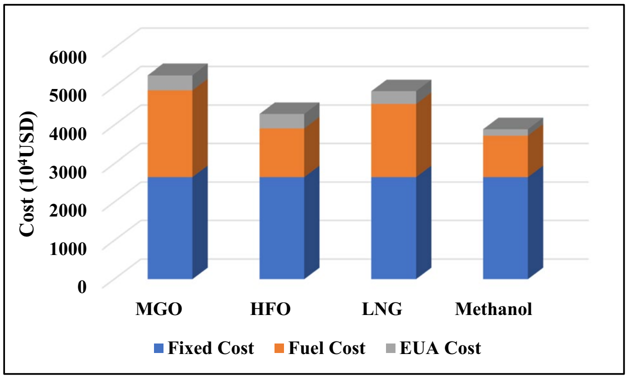

**Fig. 4** Total cost components of the selected container ship using four types of fuel

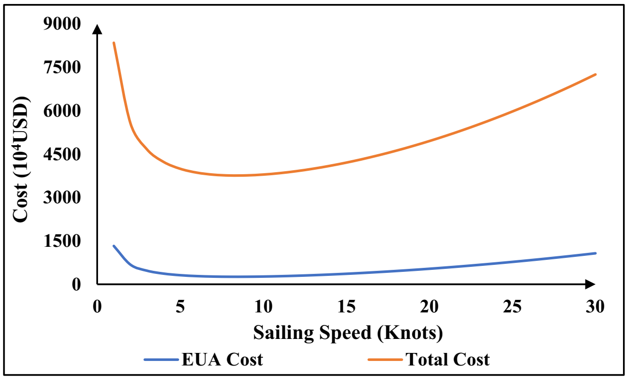

**Fig. 5** Effect of sailing speed on EUA cost and total cost of the selected container ship

**Table 11** Cost control effects of speed reduction on the selected container ship using MGO

| Sailing speed before speed reduction (knots) | Percent of speed reduction | | | |
|---|---|---|---|---|
| | 10% | 20% | 30% | 40% |
| 15.75 | 5.65% | 10.29% | 13.77% | 15.89% |
| 20 | 8.44% | 15.71% | 21.72% | 26.35% |

**Table 12** Cost control effects of speed reduction on the selected container ship using HFO

| Sailing speed before speed reduction (knots) | Percent of speed reduction | | | |
|---|---|---|---|---|
| | 10% | 20% | 30% | 40% |
| 15.75 | 4.33% | 7.87% | 10.54% | 12.17% |
| 20 | 6.72% | 12.51% | 17.30% | 20.98% |

### Scenario 2: Speed reduction

As shown in Fig. 5, the relationship between sailing speed and EUA cost of the selected container ship is a U-shaped curve, and the relationship between sailing speed and total cost of the selected container ship is a U-shaped curve. Regarding the U-shaped curve of EUA cost, the lowest point corresponds to the sailing speed of 8.36 knots. This may be due to the fact that when the EUA price is constant, the EUA cost is determined by the carbon emissions from the selected container ship within the European Economic Area (EEA). When the sailing speed is 8.36 knots, the EUA costs of the selected container ship using MGO and HFO are 668,466.38 USD and 649,283.94 USD.

Regarding the U-shaped curve of total cost, the lowest point corresponds to the sailing speed of 8.36 knots. When the sailing speed is 8.36 knots, the total cost of the selected container ship using MGO and HFO are 44,366,850.97 USD and 37,603,581.53 USD. When the sailing speed of the selected container ship is greater than 8.36 knots, speed reduction is effective in cost control of container shipping; when the sailing speed of the selected container ship is less than 8.36 knots, speed reduction is ineffective and increases its cost instead. As the average speed of the selected container ship is 15.75 knots (greater than 8.36 knots), speed reduction is effective at this time.

Reducing sailing speed of the selected container ship from 15.75 knots (average speed) and 20 knots respectively, the cost control effects of speed reduction are presented in Table 11 and 12. It can be seen that when the sailing speed before speed reduction is the same and the speed is reduced by the same percent, the cost reduction percent of the selected container ship using MGO is greater than using HFO.

It is worth noting that speed reduction may not always be environmentally and cost-effective. It is suggested that container shipping companies reduce speed within a certain range to achieve carbon reduction and cost control of container shipping. Taking the selected container ship as an example, speed reduction is environmentally and cost-effective only if the sailing speed exceeds 8.36 knots. Once the sailing speed is reduced below this threshold, speed reduction may not only fail to reduce carbon emissions and control total cost, but also increase them.

In addition to sailing speed, fuel price and EUA price also have an impact on the total cost of container shipping. However, these two factors are influenced by many external factors and cannot be the measures for container shipping companies in response to the EU ETS, so they are not considered and analyzed here.

## Conclusions

As container ships have higher speeds and generate more carbon emissions than other ship types, this paper assesses the environmental and economic impacts of including carbon emissions from maritime transport activities in the EU ETS on container shipping. Based on the EU regulation and directive, this paper constructs a cost model considering carbon emissions for container shipping. A container ship operating on the Far East to Northwest Europe route is selected for a case study. In response to the EU ETS, this paper explores some effective measures for container shipping companies to reduce carbon emissions and control total costs. The conclusions of this paper are as follows.

1. The inclusion of maritime transport activities in the EU ETS will have a direct impact on container shipping, mainly including environmental and economic impacts. Using alternative fuels and speed reduction are currently effective and common choices in response to the EU ETS.
2. Regarding alternative fuels, LNG and methanol are selected in this paper. Using LNG can achieve carbon reduction of container shipping. Using methanol can achieve carbon reduction and cost control of container shipping. Among MGO, HFO, LNG, and methanol, methanol is the most environmentally and cost-effective option. Compared to MGO, carbon reduction effects of LNG and methanol are 14.2% and 57.1%, and their cost control effects are 7.8% and 26.5%. Compared to HFO, carbon reduction effects of LNG and methanol are 11.7% and 55.8%, and cost control effect of methanol is 9.3%. The selected container ship has greater environmental benefit using LNG and has greater economic benefit using HFO.
3. The relationship between sailing speed and carbon emissions of container shipping is a U-shaped curve. Speed reduction is effective in achieving carbon reduction of container shipping only when the sailing speed is

greater than 8.36 knots. There is a U-shaped relationship between sailing speed and total cost of container shipping. Speed reduction is effective in achieving cost control of container shipping only when the sailing speed is greater than 8.36 knots. It can be found that speed reduction may not always be environmentally and cost-effective. Once the sailing speed is less than 8.36 knots, instead of achieving carbon reduction and cost control of container shipping, speed reduction will increase carbon emissions and total cost.

This paper has a few limitations which provide opportunities for future research. Firstly, the quality of the data used in this paper could be improved, and official data from IMO and EU could be more convincing. Secondly, dividing container shipping into the sailing stage and in-port stage is a bit simplified and could be further subdivided in the future. Finally, in addition to low-carbon fuels such as LNG and methanol, zero-carbon fuels such as hydrogen and ammonia can be studied in the future.

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## Declarations

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